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Characterization of Sound Power Level Spectra Produced by HVAC Chillers with Double Helical Rotary Screw Compressors Under Various Operating Conditions

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Characterization of Sound Power Level Spectra Produced by HVAC Chillers with Double Helical Rotary Screw Compressors Under Various Operating Conditions

by

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Abstract

Characterization of Sound Power Level Spectra Produced by HVAC Chillers with Double Helical Rotary Screw Compressors Under Various Operating Conditions

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Heating, ventilating, and air conditioning (HVAC) chiller units with double helical rotary screw compressors, or screw chillers, have been in common use since the mid-to-late 1980s in facilities such as schools, office buildings, and hotels. Sound level data for this type of equipment is generally available through the manufacturer on a broadband (often A-weighted) or octave-band basis. However, screw chillers are known to produce sound spectra with prominent narrow-band components that are not adequately described by broad-band or even octave-band data. Sound spectra with prominent narrow-band components are typically perceived as more objectionable than broadband sound spectra, when experienced at equivalent broadband sound levels.

The object of this study is to take the first steps towards developing empirical correlations that will yield typical sound power level (PWL) spectra for air- and water-cooled screw chillers under specified operating conditions. Such correlations would be

useful to acousticians, mechanical engineers, and architects when they are working on the design of a facility that will be served by a screw chiller, which may be in close proximity to sound-sensitive areas. Similar empirical correlations have been developed for HVAC chillers with other types of compressors, and for many other types of mechanical and industrial equipment, but to-date, there are no such correlations in common use for screw chillers.

PWL was calculated for eleven screw chillers in the Austin, Texas area, using the two-surface method. As much as possible, measurements were taken at each chiller unit under multiple operating conditions, for a total of twenty data sets. PWL was calculated for each set of measurements on a one-third-octave-band basis, and this was used to calculate the octave-band and broad-band PWL, as well as the Sound Quality Index (SQI), which is a metric describing the overall level and the prominence of any narrow-band component of a sound spectrum. The gathered data was compared against data for the same unit under different operating conditions, against data from similar units under various operating conditions, and against a previously available typical screw chiller sound spectrum. Preliminary empirical correlations were developed for sound spectra generated by air- and water-cooled screw chillers.

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Chapter 1: Introduction[1]

The goal of this project is to document the sound power level (PWL) spectra produced by Heating Ventilating and Air Conditioning (HVAC) chiller units with double helical rotary screw compressors (referred to in this report simply as screw chillers), operating under various loading conditions. PWL was calculated for eleven screw chillers (six air-cooled units and five water-cooled units) in the Austin, Texas area, based on measurements using the two-surface method [1; 2]. Measurements were taken for as many units as possible under multiple operating conditions, distinguished as percentages of the total chilling capacity of the unit. The PWL spectra gathered were compared along the following criteria:

- against data gathered at the same unit under different operating conditions;
- against data gathered for similar equipment (air-cooled versus water-cooled) in various operating conditions; and
- against the only available spectrum in use for typical screw chiller PWL.

The measured spectra were then used to characterize the screw chillers and ultimately empirical correlations were developed to describe the typical PWL spectra of air-cooled and water-cooled screw chillers, with the variables being operating parameters: total HVAC chilling capacity, operating point as a percentage of the total capacity, and screw compressor rotational velocity. These correlations yield typical one-third-octave-band sound power levels, from which octave-band and broadband levels, as

[1] The work in this chapter was part of the basis for a paper presented at Noise-Con 2017, which Daniel Alon Hemme was the primary author of, with co-authors David A. Nelson, and Preston S. Wilson.

Characterization of Sound Power Level Spectra Produced by HVAC Chillers with Double Helical Rotary Screw Compressors Under Various Operating Conditions. **Hemme, Daniel A, et al.** Grand Rapids, MI: Noise-Con 2017.

well as the Sound Quality Index (SQI) [3] can be calculated. This type of empirical correlation is reminiscent of the work of Laymon Miller in the 1950s through his retirement in 1981 [4], which are still in use in industry to this date.

The balance of this chapter will be spent explaining the function of HVAC chillers, the different types of chillers that are in use, as well as to introduce the group of empirical correlations that characterize the PWL spectra of many different types of mechanical and industrial equipment, the two-surface method of PWL measurements that was used to gather data for this thesis, and the SQI rating system. The equipment and methodology used to gather and process the data is discussed in Chapter 2. The screw chillers that were measured, and the conditions in which they are installed, are discussed in Chapter 3, and the measurements themselves are discussed and analyzed, and empirical correlations formulated, in Chapter 4. Finally, the project is summarized in Chapter 5.

Unless specifically noted otherwise, for the purposes of this report, all stated PWL values reference 1 pW, all sound pressure level (SPL) values reference 20 μPa, and all logarithmic operations are in base 10.

1.1: HVAC CHILLERS

Packaged HVAC chillers are comprised of four major components: an evaporator, a compressor, a condenser, and an expansion valve, as depicted diagrammatically in Figure 1-1. There are two basic types of chillers, classified based on the fluid with which heat is exchanged in the condenser – either water or air. Water-cooled chillers, as pictured in Figure 1-2, are typically installed in indoor mechanical rooms, and are connected to a cooling tower, which is located outdoors, through piping and pumps; the pumps are usually installed adjacent to the chiller within the mechanical room. The piping system connecting the chiller and the cooling tower is known as the condenser water loop. Air-cooled chillers, as pictured in Figure 1-3, are typically installed in outdoor equipment yards. This type of chiller contains multiple axial fans, which pull ambient air through the heat exchanger coils, and therefore does not require a separate cooling tower [5; 6].

Both types of chillers exchange chilling water with one or more Air Handling Units (AHUs) serving HVAC zones within the building. Heat is exchanged inside the AHU, between the chilled water and the air, by sending the chilled water through a coil while air is forced around the coil. The forced air is used to cool, and typically to simultaneously dehumidify, the interior of a building. The chilled water is warmed as it passes through the coil, and is then routed back to the chiller to begin the cycle again; this is known as the chilled water loop [5; 7].

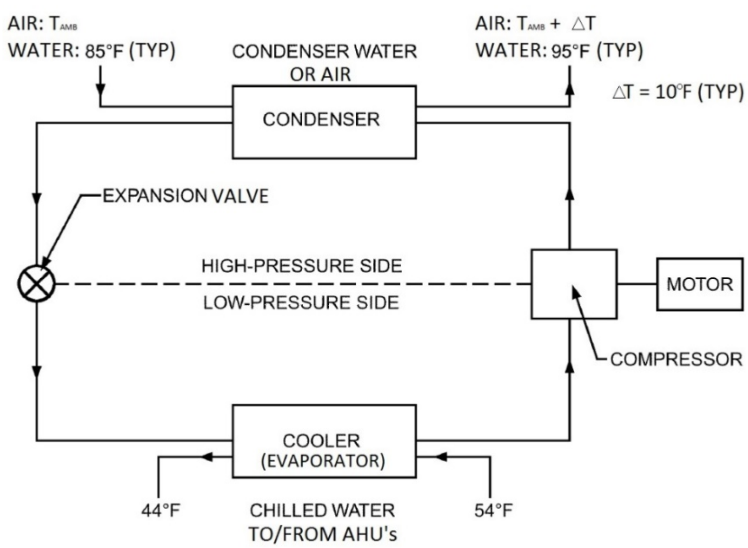

Figure 1-1: Equipment Diagram for a Basic Liquid Chiller. Adapted from ASHRAE [7].

The other major distinction between chiller units is in the type of compressor. There are several types of compressors commercially available, including: centrifugal, reciprocating, scroll, and screw, among others [8]. Each of these types of compressors has applications for which they are better suited than other types [9; 10]. A major factor in the selection of the type of compressor is the required cooling capacity. Figure 1-4 shows the approximate range in cooling capacities for which each type of compressor is oprimized; screw chillers are available in capacities ranging from approximately 80 to 800 tons [7].

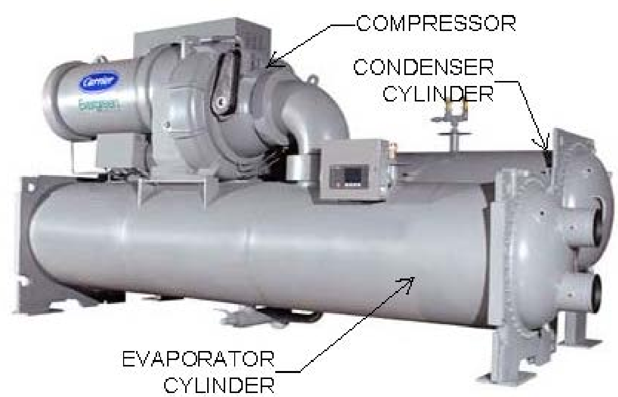

Figure 1-2: Photograph of a water-cooled chiller. Adapted from Carrier [11]

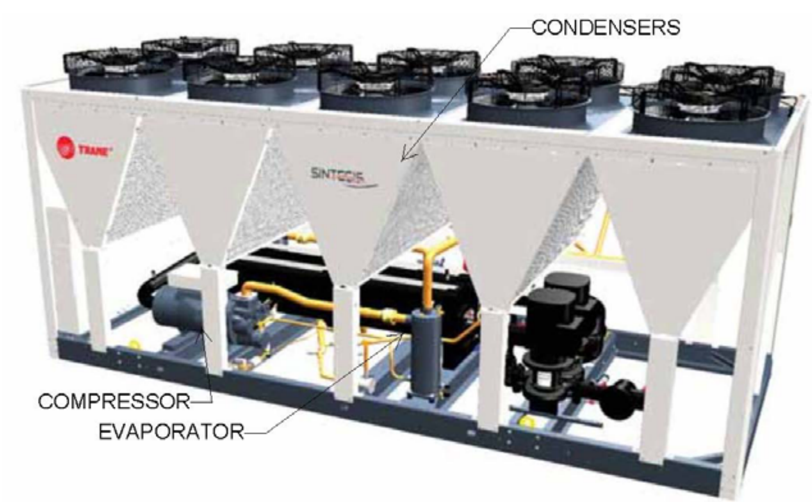

Figure 1-3: 3-D Computer Model of an Air-Cooled Compressor. Adapted from Trane [12]

For the purposes of this thesis, we are interested in air- and water-cooled chillers with screw compressors. The air-cooled chillers that were visited ranged in cooling capacity from 80 Tons to 247 Tons; the range for water-cooled chillers was 106 Tons to 248 Tons.

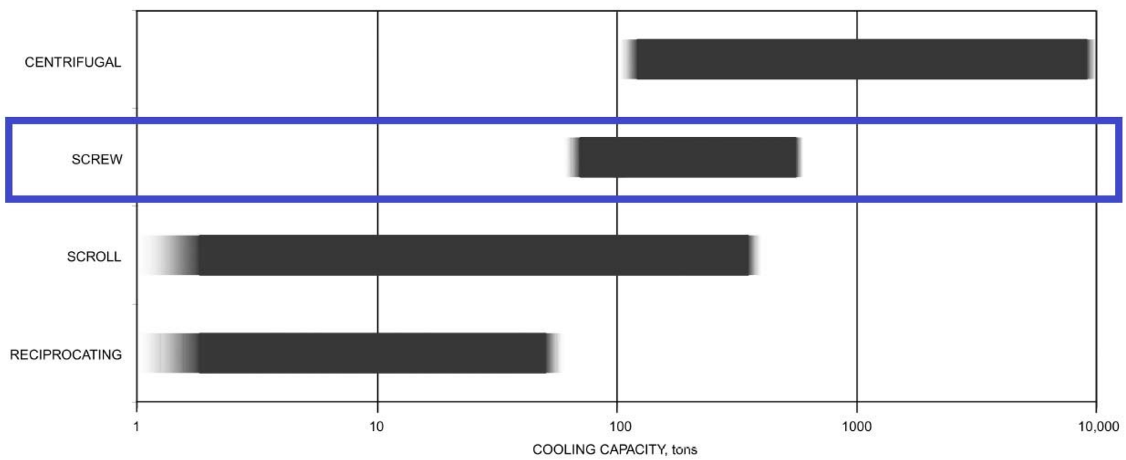

Figure 1-4: Approximate liquid chiller operation range by compressor type, with emphasis added to screw chiller range. Adapted from ASHRAE [7].

1.1A: Mechanics

Screw compressors (also known as rotary helical compressors) are positive displacement compressors (as are scroll and reciprocating compressors), which means that a volume of the refrigerant vapor is physically captured by the compressor, and forced through the unit by the action of moving parts, in the case of screw chillers the moving parts are a pair of counter-rotating rotors, the male rotor has lobes which mate with flutes in the female rotor. The number of lobes and flutes on the rotors varies with design, but combinations of 4+6, 5+6, and 5+7 (male + female) are common. The male rotor is typically directly attached to a motor, with the female rotor either driven by the same motor through synchronizing gears, or driven by the male rotor, however some newer compressor designs allow for the female rotor to be directly driven [6].

As vapor is forced through the compressor, the space available between the lobes and flutes is decreased, and the fluid is compressed. Key parts of the screw compressor are shown in Figure 1-5. In positive displacement compressors, the vapor flow rate through the unit is nearly constant, regardless of the increase of pressure in the vapor. Because of this feature, the cooling capacity of a screw chiller can be controlled, between approximately 10% and 100% of the total capacity, by varying the rotational speed of the compressor motor, and/ or by adjusting a slide valve which varies the length of the compression path [7; 8; 13].

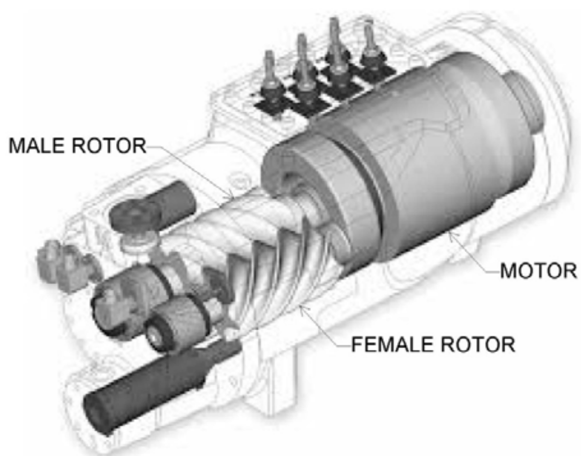

Figure 1-5: Cut-away view of a typical screw chiller, with major components labeled. Adapted from Trane [14].

1.1B: Noise Issues

Screw chillers are known to produce objectionable noise, both in terms of overall sound level, and with respect to the quality of the sound – particularly the prominent narrow band component. To some extent, these issues have been addressed by chiller manufacturers and third-party manufacturers, through a variety of methods that will be discussed in greater detail later in this section. However, in the course of securing measurement sites to visit for this research, the author encountered at least one property owner, a school district with dozens of facilities, which has a policy against the use of screw chillers, partially on the basis of the noise produced by this type of equipment.

Noise problems associated with screw chillers are well documented, and a common thread in most of the documented complaints regarding screw chiller is the narrow-band noise component, which in some cases can be heard over ambient sound levels several blocks from the installation [15]. Often the chiller units operate nearly continuously, even at night, when nearby residents would be especially sensitive to the noise generated by an outdoor chiller unit.

The center frequency of the narrow-band component corresponds to the rotational speed of the driven (usually male) rotor. This frequency, known as the Lobe Pass Frequency (LPF) can be calculated as [16]:

$$\mathrm{LPF} = \frac{nv}{60} \qquad (1.1),$$

where: LPF [Hz] ≡ center frequency of the narrow-band component,

v [RPM] ≡ rotational speed of the drive compressor rotor (usually male), and

n ≡ number of lobes on the drive compressor rotor.

Assuming typical values for ω between 3,600 and 6,000 RPM, and an n value of 4 or 5 lobes, the typical LPF is estimated to be between 240 and 500 Hz. In some cases the beating phenomenon has been observed and attributed to minor differences in the rotational speeds of the shaft and roller within the compressor [17].

Besides the rotors, other significant noise sources within screw compressors, include over-pressurization and structural resonance within the system [18; 19]. Looking past the compressors, other significant noise sources within packaged screw chiller units include axial fans situated at the top of the air-cooled units pulling air through the condensers, and pumps that are typically located relatively close to water-cooled units. Less significant sound sources include fluid flow within piping, and oil separators in both types of units [7; 20]. Sound levels produced by the fans and pumps are well documented by the work of Laymon Miller and others [4].

In general terms, low-frequency screw chiller noise is largely attributable to the compressor and the drive motor, while mid-frequencies are affected by the compressor's discharge valve, drive shaft and rotors, as well as the gas flow, and the chief source of high-frequency energy is friction at the rotors [17]. The broadband SPL produced by screw compressors typically increases with higher loading conditions [21]. Because air-cooled chillers are typically installed outdoors, often near property lines where local ordinances mandate an upper limit to the ambient sound level, these units often pose a more significant noise concern than water-cooled chillers.

Noise control of screw chillers has been investigated both in industry and academic spheres [15; 22], and acoustical treatments are available from chiller manufacturers and third party manufacturers [23]. The commonly available acoustical treatments for screw chillers can be broken up into two broad categories: those that reduce the amount of sound power generated by a screw chiller, and those that reduce the level of airborne and structure-borne sound as it is transmitted from the screw chiller to receivers located some distance away.

Acoustical treatments designed to reduce the amount of sound generated by a screw chiller include pulse diffusers, which serve to reduce noise produced at the compressed fluid discharge [15], and optional low-noise fans offered from some manufacturers for air-cooled units.

Treatment designed to reduce the level of screw chiller noise as it is transmitted include mass-loaded blankets that can be custom manufactured to fit the compressors; these are available for both air- and water-cooled chillers, and have proven successful at reducing airborne noise generated by the compressors, including the narrow-band component. Airborne noise control options for air-cooled units include fan shrouds or silencers, and in some cases barrier walls, or even full ventilated enclosures, are installed around chillers [22]. Similar considerations for water-cooled units, which are typically installed in indoors, involve constructing specially designed partitions between mechanical rooms and nearby sound-sensitive areas.

Structure-borne vibration isolation for both air- and water-cooled chillers is typically addressed by installing the units on vibration isolation pads made of neoprene or similar resilient material. In more sensitive environments, or where the chiller is installed such that low-frequency structural resonances are excited, it is necessary to install the units using isolators that include both spring and neoprene elements. Further discussion of structure-borne sound transfer is outside of the scope of this thesis.

1.2: PWL CHARACTERIZATION

PWL is the preferred metric to use for this application because unlike the alternative, SPL, PWL is independent of the acoustical environment and the distance between the source and the receiver.

PWL measurement procedures have been standardized by ASTM and ANSI/ASA. Typically PWL is calculated based on SPL measurements in a free-field environment, usually either an anechoic or hemi-anechoic chamber, or a reverberant field, usually a purpose-built reverberation chamber. Techniques are also available for PWL calculation based on sound intensity level (SIL) measurements.

In-situ measurement methods are also available [24; 25], and are necessary for equipment such as the screw chillers being discussed here, since equipment of this size and complexity cannot be easily relocated to a laboratory environment, either anechoic or reverberant.

1.2A: Historical Foundation

Laymon N. Miller (1918 – 2013) was just shy of receiving his PhD in Physics at the University of Texas at Austin in 1941, when he accepted an invitation to work at the Harvard Underwater Sound Lab (HUSL). There he met Leo Beranek (1914 – 2016), who in 1954 asked him to join the burgeoning firm of Bolt Beranek and Newman (BBN) as an acoustical consultant. Miller worked at BBN for the remainder of his career, where his focus was largely on noise and vibration issues pertaining to HVAC systems, manufacturing equipment, and transportation. In 1962, Laymon Miller became the first principal consultant at BBN. He used the sabbatical that was included with the promotion to organize about a decade's worth of experience into a noise control course targeted towards operators and regulators of manufacturing and industrial plants, and other groups with a need for understanding some noise control principles, but without the technical background. The course was continually refined, and was offered on a nearly annual basis until Miller's retirement in 1981. Since Miller's retirement, the noise control course continues to be offered by Reginald Keith, now of Hoover and Keith of Houston, Texas, a protégé of Miller from their days at BBN.

One key aspect to the noise control course, and perhaps a reason for its ongoing relevance, is the collection of empirical correlations for typical octave-band PWL spectra for mechanical and industrial equipment, including electrical generators, various types of fans, HVAC chillers with reciprocating and scroll compressors, etc., which is available in the course text. The variables of these correlations pertain to operating parameters such as rotational velocities, fluid flow rates, pressure differences, etc., which are generally known to some degree of certainty to the mechanical engineer designing the system, thus making the empirical correlations relatively easy to use as design guidelines when equipment types and operating conditions may be subject to change. The correlations derived by Laymon Miller, and other similar correlations are still in widespread use in the field of architectural acoustical consulting, and are the basis for industry-standard correlations related to HVAC noise control published by the American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) [23; 26]. Despite the importance of this group of empirical correlations, an adequate correlation has not yet been developed for screw chillers; this is due in part to the fact that Laymon Miller retired in 1981, and screw chillers did not come into prominence until the late 1980s and early 1990s.

Laymon Miller's research into screw chillers as a noise source is limited to five units operating between 80 and 90 percent of their total potential cooling output, which ranged between 100 and 300 HVAC tons, and with the drive rotor rotating at approximately 3600 RPM [4]. It is not made clear if the units surveyed by Miller were air-cooled, water-cooled, or a combination of the two. Miller did not publish a correlation in the same form as he did for most of the types of equipment that he studied, describing anticipated PWL produced by screw chillers as a function of equipment parameters. Instead, he published a typical PWL spectrum for the units that he surveyed, which is displayed in Table 1-1. This approach, while understandable due to the amount of data available at the time of Miller's retirement, is less than desirable, as the spectrum provided is only at octave-band resolution, and there is no distinction made between air-cooled and water-cooled units, or provisions to account for variations in operating conditions [4].

Table 1-1: Typical Screw Chiller PWL Spectrum, as published by Laymon Miller [4]

Frequency [Hz]	**31**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
PWL ref. 1pW [dB]	78	84	88	100	97	93	88	83	81
Broadband Metric	**dB**	**dBA**							
PWL ref. 1pW [dB]	103	98							

Knowledge of the expected PWL spectrum generated by a piece of equipment, or a group of several pieces of equipment, can inform the architect's decision to design a mechanical room enclosure in a certain manner with respect to the ambient noise level requirements in adjacent areas. This information can also be useful when noise generating equipment is, or will be, located outdoors in close proximity to a residential area or similar sound-sensitive location, and a decision must be made regarding how best to maintain acceptable sound levels within these areas.

In most cases acoustics-related data available from equipment manufacturers is nebulous at best. In the worst cases the data is a single broadband decibel value with no indication on weighting, or information regarding the measurement conditions or calculation assumptions. In best-case scenarios, octave-band PWL data, measured and calculated according to a stated industry accepted standard, is available for specified equipment operating conditions. Octave-band level data is sufficient for many types of equipment, but the narrow-band peaks that are prominent in screw chiller spectra require minimum one-third-octave band resolution in order to be adequately described. [27]

1.2B: The Two-Surface Method of PWL Measurement

The two-surface method of PWL measurement was selected for this study because it is the only standardized in-situ measurement technique based on SPL measurements that does not require the equipment under test to be deactivated. The two-surface method requires that RMS SPL measurements be taken over as much of the exposed surface area of the unit under test as possible, at two known distances from the source. The pair of measurements are taken over inner and outer measurement surfaces, forming concentric parallelepipeds, as depicted in Figure 1-6. The surface areas for the inner and outer measurement surfaces can be calculated as:

$$S_1 = ab + 2bc + 2ac, \qquad \text{and} \qquad S_2 = de + 2df + 2ef \ [\mathrm{ft}^2] \qquad (1.2),$$

where: S_1 [ft^2] ≡ surface area of the inner measurement surface,

S_2 [ft^2] ≡ surface area of the outer measurement surface, and

a, b, c, d, e & f [ft] ≡ dimensions as indicated in Figure 1-6.

The sound power level for an arbitrary sound source in a semi-reverberant space is calculated as:

$$L_w = L_p - 10\log\left(\frac{1}{S} + \frac{4}{R}\right) - 10.5 \ [\mathrm{dB}] \qquad (1.3),$$

where: L_w [dB] ≡ calculated sound power level,

L_p [dB] ≡ measured sound pressure level,

S [ft^2] ≡ area into which the sound power, L_w, radiates, and

R [ft^2] ≡ room constant.

The room constant, R, is defined as:

$$R = \frac{S_* \alpha_*}{1 - \alpha_*}$$

where: S_* [ft^2] ≡ total surface area of the room, and

α_* ≡ average acoustical absorption coefficient of the room surfaces.

The room constant relates to the classic Sabine equation for reverberation time in an enclosed space:

$$T_{60} = 0.049\frac{V\!\!\!/}{A}\,[\text{dB}] \quad (1.4),$$

where: T_{60} [s] ≡ reverberation decay time (60 dB),

$V\!\!\!/$ [ft^3] ≡ volume of the room,

A [ft^2] = $S_*\alpha_* + V\!\!\!/\alpha_{air}$ ≡ total acoustical absorption within a room, and

α_{air} ≡ acoustical absorption coefficient due to air,

Assuming a relatively reverberant space, and hence a relatively low α_*, the room constant, R, approximates the total acoustical absorption, A. These conditions are typical for an enclosed mechanical room, but not necessarily so for an outdoor equipment yard. Regardless, the Room constant term will cancel out, as will be shown shortly.

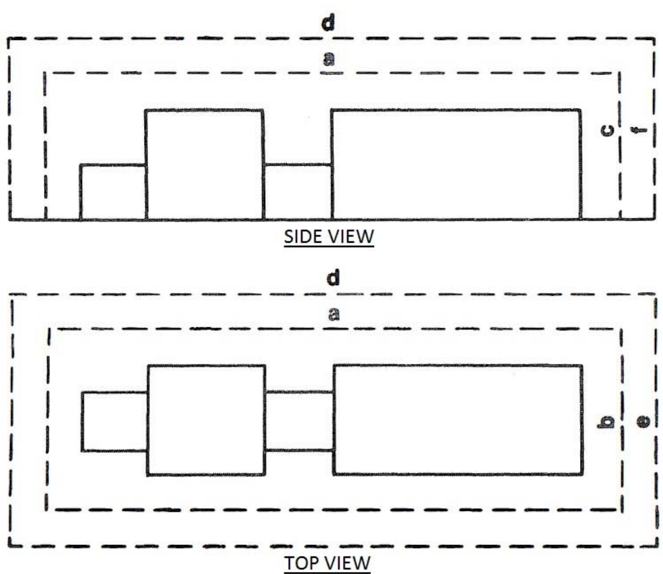

Figure 1-6: Diagram of a typical measurement scenario, showing inner and outer measurement surfaces. Adapted from Diehl [28].

Clearly, in the case of the screw chillers being discussed, the same sound power passes through the inner surface, S_1, as through the outer surface, S_2. In other words:

$$L_w = L_1 - 10\log\left(\frac{1}{S_1} + \frac{4}{R}\right) - 10.5 = L_2 - 10\log\left(\frac{1}{S_2} + \frac{4}{R}\right) - 10.5 \text{ [dB]} \qquad (1.5),$$

where: L_w [dB] ≡ calculated sound power level,

L_1 [dB] ≡ RMS sound pressure level measured over the inner measurement surface, and

L_2 [dB] ≡ RMS sound pressure level measured over the outer measurement surface.

Equation (1.5) can be simplified by solving for L_1 and L_2, subtracting the two equations and combining the logarithmic terms to arrive at:

$$L_1 - L_2 = \Delta L_p = 10\log\left(\frac{\frac{1}{S_1} + \frac{4}{R}}{\frac{1}{S_2} + \frac{4}{R}}\right) \qquad \text{[dB]} \qquad (1.6),$$

which can be further reduced to:

$$\left(\frac{\frac{1}{S_1} + \frac{4}{R}}{\frac{1}{S_2} + \frac{4}{R}}\right) = 10^{\frac{\Delta L_p}{10}} = K \qquad (1.7),$$

and then rearranged as:

$$\frac{1}{S_1} + \frac{4}{R} = K\left(\frac{1}{S_2} + \frac{4}{R}\right) \qquad (1.8).$$

At this point, it becomes relatively straight-forward to isolate the room constant, R, by combining like terms:

$$\frac{4}{R} - \frac{4K}{R} = \frac{K}{S_2} - \frac{1}{S_1} \qquad (1.9),$$

and simplifying:

$$\frac{4}{R} = \frac{\frac{K}{S_2} - \frac{1}{S_1}}{1-K} \qquad (1.10).$$

The form of Equation (1.5) can be manipulated as follows:

$$L_w = L_1 - 10\log\left(\frac{1}{S_1} + \frac{4}{R}\right) - 10.5$$

$$= L_1 - 10\log\left(\frac{\frac{S_1}{S_1} + \frac{4S_1}{R}}{S_1}\right) - 10.5$$

$$= L_1 - 10\log\left(1 + \frac{4S_1}{R}\right) + 10\log(S_1) - 10.5 \qquad (1.11),$$

and the environmental correction term, C, can be defined as:

$$C = 10\log\left(1 + \frac{4S_1}{R}\right) \qquad (1.12),$$

into which, the $\frac{4}{R}$ term from Equation (1.10) can be inserted, and then the equation can be manipulated to arrive at:

$$C = 10\log\left(1 + \frac{\frac{K}{S_2} - \frac{1}{S_1}}{1-K} S_1\right)$$

$$= 10\log\left[K\left(\frac{\frac{S_1}{S_2} - 1}{1-K}\right)\right] \qquad (1.13)$$

Equation (1.5) can now be rewritten entirely in terms of the inner and outer measurement surface areas, and the RMS SPL measurements over the same surfaces:

$$L_w = L_1 - C + 10\log(S_1) - 10.5 \qquad (1.14),$$

where: $C = 10\log\left(K\frac{\frac{S_1}{S_2}-1}{1-K}\right) \equiv$ correction term for the measurement environment, and

$K = 10^{\frac{L_1-L_2}{10}}$.

In the equations discussed above, S_1 and S_2 represent the total measurement surface areas on all five exposed sides of the chiller unit being measured – two short sides, two long sides and the top. Each pair of constituent measurement surfaces, $S_{1,i}$ and $S_{2,i}$, was surveyed individually, and the measured PWL values for each total measurement surface was calculated as:

$$L_1 = 10\log\left(\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{L_{1,i}}{10}}\right) \quad \text{and} \quad L_2 = 10\log\left(\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{L_{2,i}}{10}}\right) \quad (1.15),$$

where $L_{1,i}$ and $L_{2,i}$ are the measured SPL values for the ith inner and outer constituent measurement surfaces, respectively, and n is the total number of constituent areas measured for the particular chiller unit [25].

A correction was made in all cases where the total of the constituent surface areas did not fully cover the theoretical measurement surface, due to piping or other equipment or connections, or some other obstacle that blocked access to a side or a portion of a side. The discrepancy due to missing measurements from blocked or inaccessible surface areas was accounted for by adjusting the total calculated PWL as follows:

$$L_{w*} = L_w + 10\log\left(\frac{S_{1,t}}{S_1}\right)\ [dB] \qquad (1.16),$$

where L_{w*} is the total calculated PWL, L_w is the PWL as calculated based on the accessible measurement surface areas per Equation (1.13), and S_1 and $S_{1,t}$ are the total areas of the measured and theoretical inner surfaces, respectively [25]. Note that if $S_1 = S_{1,t}$ – in other words, if the entire surface area of the chiller unit is surveyed – then the logarithmic term in Equation (1.15) disappears, and $L_{w*} = L_w$. For this reason, all total screw chiller PWL values calculated in the spreadsheet, and reported herein are L_{w*} values.

Error bounds for the collected data and resulting empirical correlations are unknown, but are assumed to be such that the correlations are suitable for use as a preliminary first step towards development of a set of correlations that are reliable for use in industry. It is further assumed that the correlations presented would be more accurate, over a wider range of equipment cooling capacities and operation points, if significantly more units were available for measurement, over a more varied range of operating conditions. The compromises and limitations inherent to the measurement procedure and data analysis are discussed in greater detail later in this thesis.

1.3: SOUND QUALITY INDICATOR CALCULATION

Sound Quality Indicator (SQI) is a single-number descriptor, which can be used to quantify subjective quality of a given one-third-octave-band spectrum, based on overall level and the prominence of narrow-band components present. This metric was developed and standardized by the American Heating and Refrigeration Institute (AHRI) in ANSI/AHRI Standard 1140 [3].

The SQI calculation procedure requires one-third-octave band sound power data, band-limited between the 100 Hz and 10 kHz one-third-octave bands, which is analyzed and weighted to account for frequency distribution and discrete narrow-band components. In general, a higher SQI value indicates more prominent narrow-band components in the spectrum and/or a higher overall level, and correspondingly lower subjective sound quality. Valid comparisons of SQI values for various pieces of equipment can be made only if all of the pieces of equipment are of the same general type and thermal capacity [3]. For this reason, SQI values for air-cooled and water-cooled screw chillers are compared separately in this thesis.

The spectrum analysis consists of identifying all one-third-octave bands with sound levels exceeding the average of the two adjacent bands by 1.5 dB or greater. The sound levels of the identified one-third-octave bands are adjusted as follows:

$$L' = L - P + 10\log\left(10^{(D+B)} + 1\right) \quad (1.17),$$

where: $B = 76.2794 - 75.7436Y + 29.9803Y^2 - 6.13769Y^3 + 0.691827Y^4 - 0.0408822Y^5 + 0.000991561Y^6$,

$D = \log(10^{P/10} - 1)$,

F [Hz] ≡ one-third-octave band center frequency, where 125 Hz ≤ $F \leq 8{,}000$ Hz,

L [dB] ≡ measured sound level for the one-third-octave band,

L' [dB] ≡ tone adjusted sound level for the one-third-octave band,

P [dB] ≡ projection above the average of the two adjacent one-third-octave bands, and

$Y = \ln(F)$.

The rating indices for each tone-corrected one-third-octave-band sound level are determined according to tabulated values, provided in Appendix C. For non-integer data points, interpolation within the table is necessary.

Finally, the SQI can be calculated as:

$$SQI = K + 10\log(\textstyle\sum I) \qquad (1.18),$$

where: $\sum I$ ≡ Arithmetic sum of rating indices for the one-third-octave bands from 100 Hz to 10,000 Hz,

I_m ≡ Maximum one-third-octave band rating index from 100 Hz to 10,000 Hz

$K = 11.83888 - 4.94569\ln(X) + 0.614812[\ln(X)]^2$, and

$X = \frac{\sum I}{I_m}$.

SQI is sensitive to absolute level, as well as relative levels of one-third-octave-bands compared with adjacent bands. The magnitude of the tabulated rating indices increase with the magnitude of the tone adjusted PWL, but the rate of the increase also increases with the magnitude of the tone adjusted PWL, particularly in the frequency range of 1,600 Hz to 8,000 Hz.

For comparison, the SQI for three groups of three theoretical sound spectra are compared in Figure 1-7. The first spectrum in each group, shown as a solid line, is broadband; the second spectrum, shown as a dashed line, contains a low-level noise floor, and a peak in the 1,000 Hz one-third-octave-band that is 25 dB above the noise floor; and the third spectrum, shown as a dot-dashed line, is a logarithmic sum of the first two spectra. In the first group, shown in orange, the broadband noise is at a level of 60 dBA, and the low-level noise floor is at 35 dB across the audible frequency range. In the second group, shown in purple, both the broadband noise and the low-level noise floor are 3 dB above the first group. In the third group, shown in red, the broadband noise and low-level noise floor are 3 dB below the first group.

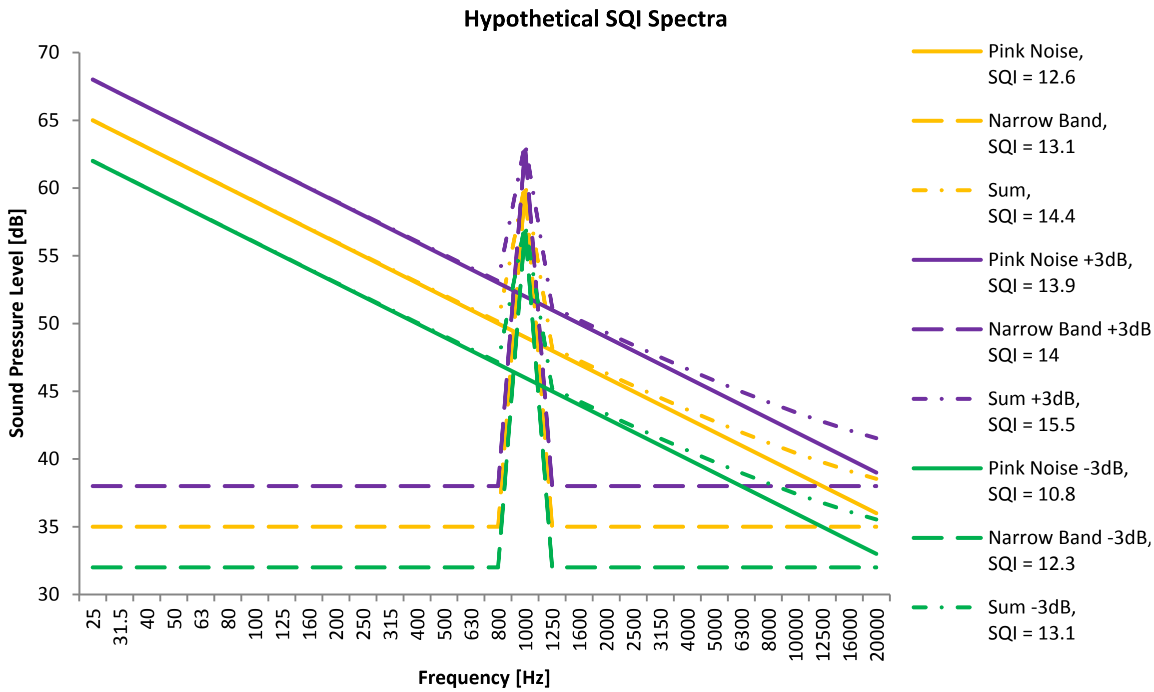

Figure 1-7: Comparison of hypothetical spectra of various shapes – pink noise, low-level background , and at various levels, and the resulting SQI values.

The resulting SQI values are further compared in Figure 1-8. It is shown that for each group of spectra, which are color coded the same as in Figure 1-7, the broadband spectrum, indicated with a square marker, has the lowest SQI value, the spectrum with the low-level noise floor and a spectral peak at 1 kHz, indicated with a triangular marker, has an intermediate SQI value, and the sum of the previous spectra, indicated with a diamond shaped marker, has the highest SQI value. Additionally, the group of spectra with the lowest overall level exhibit the lowest SQI values, and the group of spectra with the highest overall level exhibit the highest SQI values.

It is interesting to note that the spread between the narrow band and summation spectra versus the broadband spectra are greatest for the group of spectra that is lowest in overall level, and smallest for the group of spectra that is highest in overall level. In other words, the effect of a prominent narrow-band component on the SQI rating is most pronounced when the overall level is relatively low.

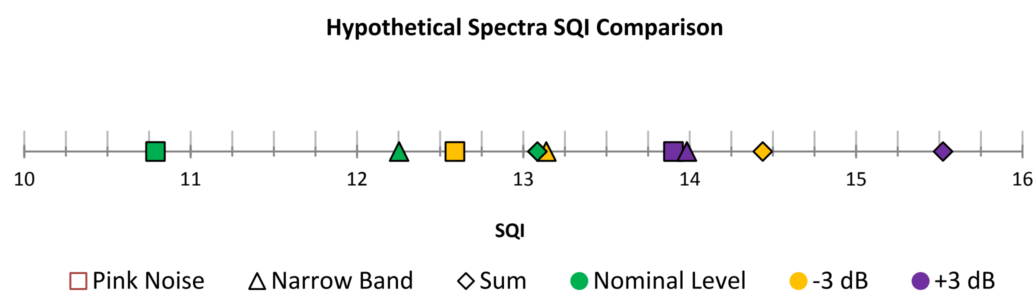

Figure 1-8: Comparison of SQI values resultant from the hypothetical spectra shown in Figure 1-7.

Chapter 2: Equipment & Methodology[2]

Measurements and analysis were undertaken following, primarily, the requirements of the test method described in ASTM 1124-10: Standard Test Method for Field Measurement of Sound Power Level by the Two-Surface Method [25]. The minimum hardware and data processing requirements are described in this standard. This test method was supplemented with other standardized procedures, in order to qualify and calibrate the measurement equipment and analysis software. The effect of the microphone windscreens was quantified per AHRI 250 Appendix D [29], and the response of the two microphones used was compared per ASTM 1124, paragraph 7.1.1 [25].

The measurement system was calibrated for precision and accuracy. Precision is defined here as general agreement between measurements taken on the same piece of equipment, by the same method, in various field locations. Accuracy is defined here as agreement between measurements taken on the same piece of equipment under field and laboratory conditions, or between field measurements and anticipated sound levels provided by the factory for a specific piece of equipment. A diagrammatic representation of the relationship between precision and accuracy is shown in Figure 2-1.

2.1: Project Planning

Measurements were carried out under the perceived intent of ANSI/AHRI Standard 350-2008 [30], and ANSI/AHRI Standard 370-2011 [31]. Equipment used was in conformance with the standards, and, while not laboratory-grade equipment, it was the equipment available. Unweighted octave-band PWL values are reported for octave bands

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[2] The work in this chapter was part of the basis for a paper presented at Noise-Con 2017, which Daniel Alon Hemme was the primary author of, with co-authors David A. Nelson, and Preston S. Wilson.

Characterization of Sound Power Level Spectra Produced by HVAC Chillers with Double Helical Rotary Screw Compressors Under Various Operating Conditions. **Hemme, Daniel A, et al.** Grand Rapids, MI: Noise-Con 2017.

centered between 63 Hz and 8 kHz, unweighted one-third-octave band PWL levels are reported for one-third-octave bands centered between 50 Hz and 10 kHz, the unweighted, A-weighted, and C-weighted PWL values are reported, as is the SQI, calculated per ANSI/AHRI Standard 1140 [3]. The major deviation between the test procedure in these standards and the procedure carried out for this project is the requirement in the standards that the PWL measurements be performed per AHRI Standard 220, in a reverberation chamber, or per ISO 3745 in a hemi-anechoic environment; as previously discussed, PWL was measured for this project according to the two-surface method, in-situ, as standardized in ASTM E1124 [25].

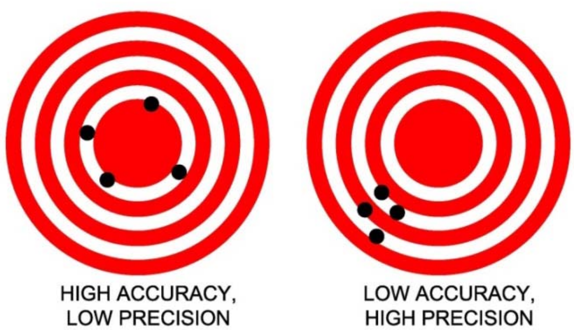

Figure 2-1: Accuracy vs. Precision Diagram. High accuracy with low precision shown at left; low accuracy with high precision shown at right.

The measurement procedure was developed with guidance of ANSI S12.1-1983 (reaffirmed 2011) [32]. This measurement procedure, and the equipment used, are best described as a survey method, as opposed to a precision or general purpose method. The decision to pursue a survey method was made based on the available budget, timeframe, and equipment. ANSI S12.1 encourages the consideration of appropriate parts of other standards which deal with similar sound sources or measurement procedures, which has been accomplished in the planning and execution of this measurement procedure.

The data recording form found in ANSI/ AHRI Standard 575 – Method of Measuring Machinery Sound Within an Equipment Space, Appendix C2 [33] was used as a primary basis for the Site Visit Data Sheets developed for this thesis. The Site Visit Data Sheets, filled out for each site visit, are shown in Appendix A. Further guidance in equipment selection and use, as well as the reporting of collected data was found in ANSI S1.13-2005 [34], ANSI S12.18-1994 (Reaffirmed 2009) [35], and ASTM E1780-12 [36]. It should be noted that the measurements taken for this thesis were not made in strict conformance with the sources used for guidance in development of the Site Visit Data Sheets. Most significantly, it was not possible to turn off any of the screw chillers being measured, in order to measure ambient sound pressure levels within the equipment enclosures due to sound sources other than the screw chiller; and it was not always possible to avoid taking measurements within one meter of a wall or other plane surface larger than one square meter, as required in the standard. Also most of the referenced standards require stationary microphones at proscribed distances from other microphones, and from the screw chiller being measured; all of the measurements for this thesis were made using the two-surface method, as previously described.

2.2: EQUIPMENT SETUP

The experimental equipment setup consisted of hardware and software that was configured to record audio at the screw chiller installation site according to the two-surface method, and process the recorded audio to generate PWL data at one-third-octave-band frequency resolution.

2.2A: Hardware

The requirements of the measurement apparatus are prescribed in ASTM 1124 [25]. These requirements include a matched and calibrated pair of microphones, an audio recording device and frequency spectrum analyzer with minimum 0.1 dB resolution, and a microphone mounting fixture, or boom, that must be made of non-conducting material and may include a piece of soft foam or similar material at the tip to minimize the effect of direct contact between the boom and presumably vibrating surface of the screw chiller. A diagram, modified from ASTM 1124 to better reflect the system used, is shown diagrammatically in Figure 2-2.

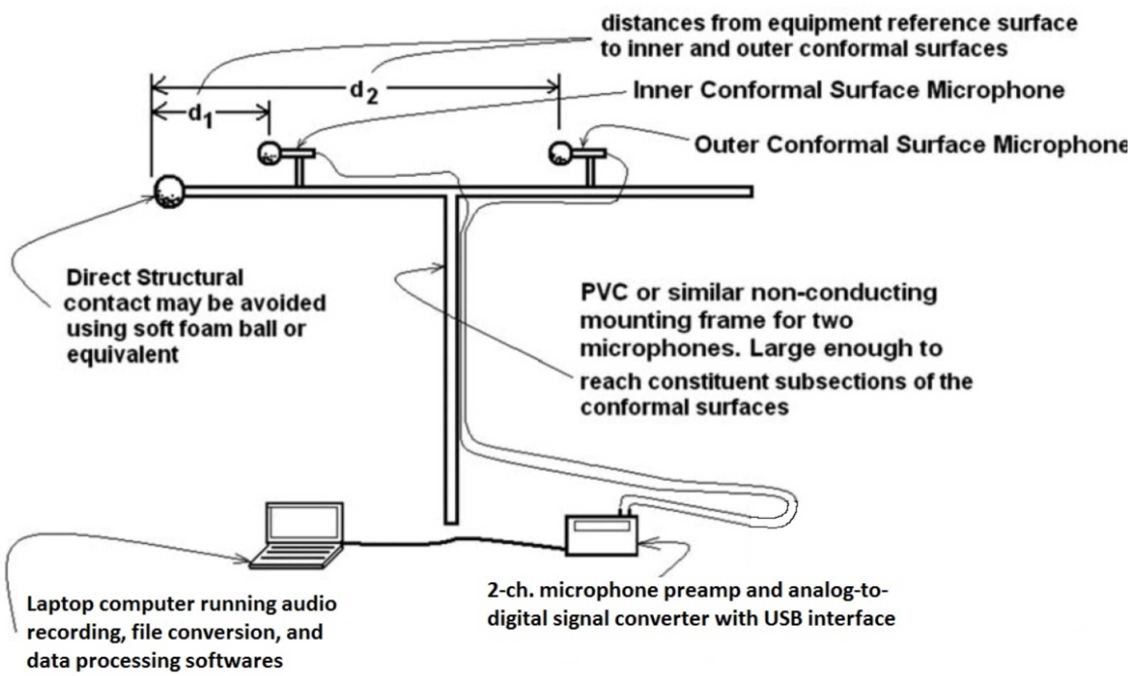

Figure 2-2: Test measurement setup diagram. Adapted from ASTM E1124-10 [25].

The microphones used were Audix model TM1-PLUS, Type II reference microphones with ¼" omni-directional capsules, model MC19 shock-mounts and model WST1 windscreens. The microphones were installed on a fiberglass boom for all locations where there was space available to deploy it; the minimum length of the extendable fiberglass boom was 74", the maximum extension was 141". At locations without sufficient space for the fiberglass boom, a 38” wooden boom was used instead. The inner measurement surface microphone mounted on the fiberglass boom is shown in Figure 2-3. The microphones were calibrated before each measurement session using a 94 dB, 1 kHz tone generated by an ACO Pacific model 511E Type 1L speakerphone-style calibrator. Audio signals from the microphones were routed to a Presonus model 44VSL 4-channel preamplifier and analog digital converter with USB connectivity to a laptop computer.

Figure 2-3: Detail of Front of the Test Measurement Boom Apparatus

2.2B: Software

Audio was recorded to the laptop computer as 16 bit two-channel WAV files, at a sampling rate of 44.1 kHz, using Presonus Studio One v.2.6.0.24200 audio recording software, and was then imported into a custom-made data processing application running on the National Instruments LabView platform. The data acquisition and processing details are discussed further in Appendix B. At a basic level, SPL measurements from all measurement surfaces, along with calibration measurements for the particular preamplifier gain settings used for the same set of measurements were processed within the application. A spreadsheet was automatically created in Microsoft Excel with one-third-octave-band, octave-band, and broadband flat, A-weighted, and C-weighted RMS SPL values for each measurement surface. Dimensional information for each measurement surface was input into the spreadsheet, and PWL was calculated within the spreadsheet as discussed in Chapter 1, according to the following equation:

$$L_w[dB] = \begin{cases} L_1 - 10\log\left[\left(\frac{10^{\frac{(L_1-L_2)}{10}}}{10^{\frac{(L_1-L_2)}{10}}-1}\right)\left(\frac{S_2-S_1}{S_2}\right)\right] + 10\log(S_1)\,, & L_1 \geq L_2 + 0.1 \\ 0, & L_1 < L_2 + 0.1 \end{cases} \quad (2.1),$$

where: L_1 and L_2 are the measured SPL values for the inner and outer measurement surfaces, respectively, and S_1 and S_2 are the surface areas of the inner and outer measurement surfaces, respectively [25].

2.3: EQUIPMENT TESTING & CALIBRATION

The measurement system was tested and calibrated using a Brüel & Kjær model 4204 reference sound source (RSS), which is capable of producing approximately 96 dBA PWL, with a frequency response from 100 Hz to 20 kHz that approximates the spectrum shown in Figure 2-4 [29; 37; 38].

System calibration and testing, using the RSS, was undertaken at several locations including the UT anechoic chamber, a residential driveway and back yard, a local elementary school basketball court, and the UT Intramural Fields. It should be noted that the UT anechoic chamber is qualified only down to 125 Hz, due to the physical dimensions of the space [39].

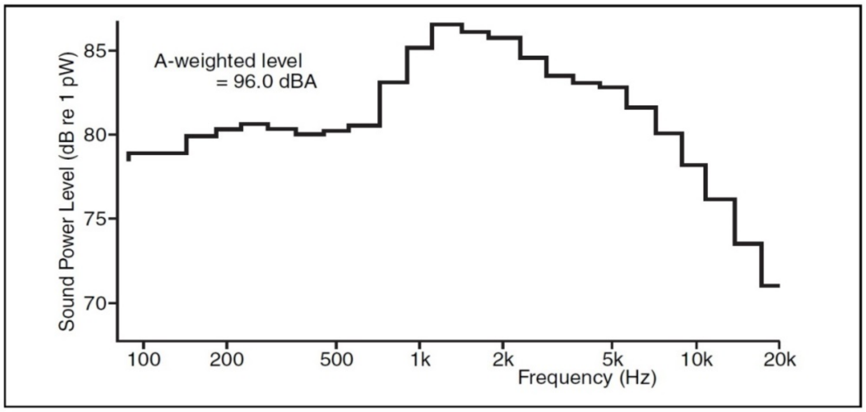

Figure 2-4: Typical PWL Spectrum Generated by the Reference Sound Source. Adapted from Brüel & Kjær [38].

2.3A: Windscreen Correction

Validation of microphone windscreens used was undertaken following to the procedure described in AHRI 250 Appendix D [29], although the fully anechoic chamber on the UT Austin campus was used in lieu of the hemi-anechoic chamber called for in the standard. This procedure consisted of calibrating both microphones, using the same calibrator, arranging the microphones equidistant to the RSS, and oriented towards the center of the RSS, within the anechoic chamber, and finally recording 60 second samples using each microphone, first without, and then with the windscreen installed. The resulting one-third-octave band average SPL values for each microphone/ windscreen assembly were then analyzed as:

$$\Delta_{WS} = \mathrm{SPL}_{w/o} - \mathrm{SPL}_{w/} \qquad (2.2),$$

where: Δ_{WS} [dB] ≡ difference in SPL due to the windscreen,

$\mathrm{SPL}_{w/o}$ [dB] ≡ measured SPL without windscreen installed, and

$\mathrm{SPL}_{w/}$ [dB] ≡ measured SPL with windscreen installed.

The one-third-octave band Δ_{WS} values for both microphones are shown in Figure 2-5. It is shown that the windscreens meet the requirements of ANSI/AHRI Standard

370-2011 [31]: the windscreens must not affect the response of the microphones by more than ±1 dB between 20 Hz and 4 kHz, or by more than ±1.5 dB above 4 kHz. It is clear that the effect of the windscreen is insignificant at 8 kHz and below. Above 8 kHz, the windscreen attenuates sound at a rate of approximately 1 dB per octave. This high-frequency deficiency in the measurement setup is addressed by not reporting PWL values above the 8 kHz octave band (10 kHz one-third-octave band). The discrepancy between the two data sets below 63 Hz can be attributed to the low-frequency limitations inherent to the anechoic chamber used for the measurement. Between 63 Hz and 8 kHz, the value of Δ_{WS} for both microphones was within the range of ±0.15 dB.

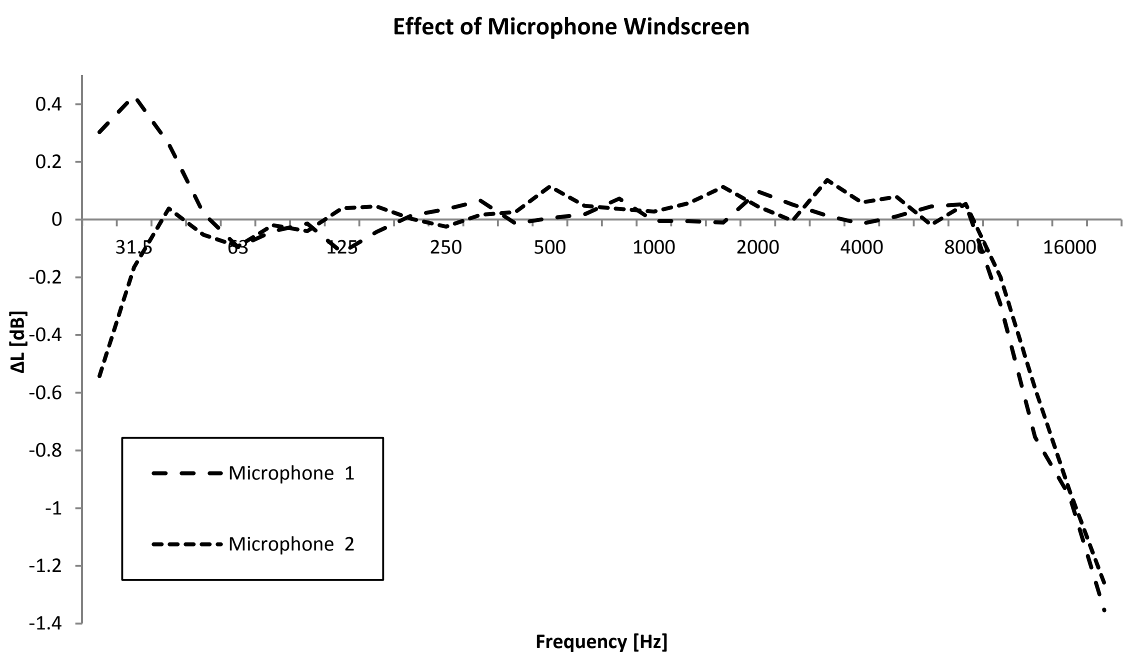

Figure 2-5: Effect of the installed windscreen for both measurement microphones

2.3B: Microphone Correction

The audio signal paths for the two measurement surfaces were calibrated against each other using the procedure described in ASTM 1124, paragraph 7.1.1 [25]. This calibration procedure consisted of connecting the microphones to the same microphone preamplifier and analog-to-digital converter that was subsequently used at the site measurements, and calibrating both channels using the same calibrator. The microphones were placed equidistant from the RSS within the anechoic chamber, and audio was recorded concurrently to separate channels over a 60 second period. The resulting average SPL values were analyzed at a one-third-octave band frequency resolution as follows:

$$\Delta_{mic} = \mathrm{SPL}_1 - \mathrm{SPL}_2 \qquad (2.3),$$

where: Δ_{mic} [dB] ≡ difference in SPL between the two microphones,

SPL_1 [dB] ≡ measured average SPL from microphone number 1, and

SPL_2 [dB] ≡ measured average SPL from microphone number 2.

The resulting Δ_{mic} values are shown in Figure 2-6, and tabultated in Table 2-1. A low-frequency deviation is observed in this data set, which can be attributed to low-frequency limitations inherent to the anechoic chamber used for the measurements, similar to the results of the windscreen calibration. Above 40 Hz, the value of Δ_{mic} is limited to the range of ±0.2 dB.

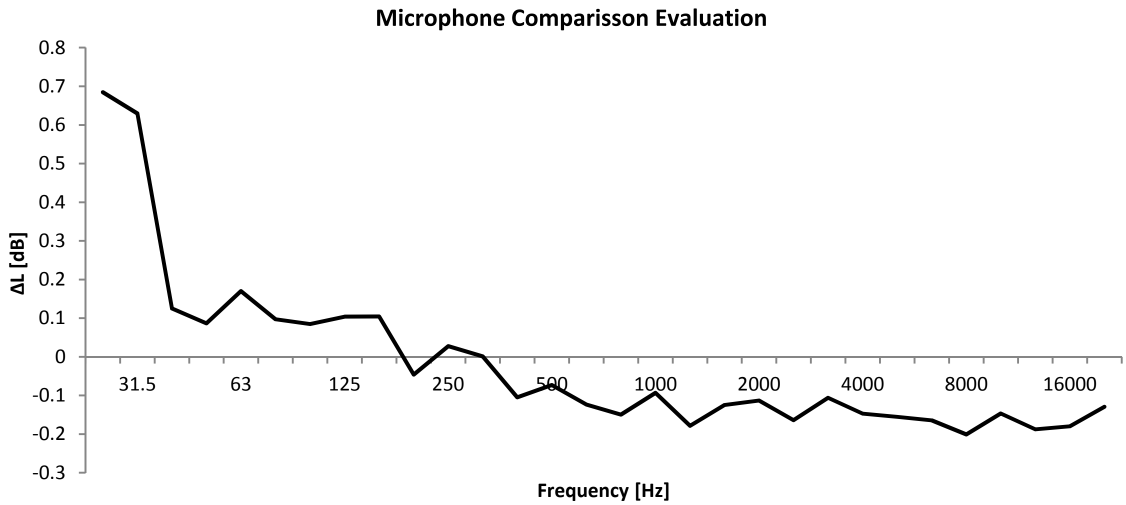

Figure 2-6: Difference in response between the two measurement microphones

Table 2-1: Paired Microphone Calibration Data

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
Mic #1	0.30	0.43	0.26	0.02	-0.10	-0.04	-0.01	-0.11	-0.04	0.01
Mic #2	-0.54	-0.17	0.04	-0.05	-0.09	-0.02	-0.04	0.04	0.05	0.00
Mic Comp.	0.68	0.63	0.12	0.09	0.17	0.10	0.08	0.10	0.10	-0.05
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
Mic #1	0.04	0.07	-0.01	0.01	0.02	0.07	0.00	-0.01	-0.01	0.10
Mic #2	-0.02	0.02	0.03	0.11	0.05	0.04	0.03	0.06	0.11	0.05
Mic Comp.	0.03	0.00	-0.11	-0.07	-0.12	-0.15	-0.09	-0.18	-0.12	-0.11
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
Mic #1	0.05	0.01	-0.01	0.01	0.05	0.05	-0.29	-0.75	-0.96	-1.35
Mic #2	0.00	0.14	0.06	0.08	-0.02	0.05	-0.20	-0.58	-0.94	-1.26
Mic Comp.	-0.16	-0.11	-0.15	-0.16	-0.16	-0.20	-0.15	-0.19	-0.18	-0.13

2.3C: System Calibration

The measurement system was calibrated for accuracy by comparing PWL measurements of the RSS taken in the UT anechoic chamber following ANSI-ASA S12.55 [40] as closely as possible with the equipment available against PWL measurements of the RSS taken in various environmental settings using the two-surface method measurement setup that would later be used later at the site visits. The measurement system was calibrated for precision by comparing PWL measurements of the RSS taken in various environmental settings and various gain settings against each other. The measurement system was calibrated for repeatability by comparing several PWL measurements of the RSS taken in a particular environmental setting against each other.

PWL measurements in the anechoic chamber were accomplished by positioning the RSS near the center of the chamber grid floor, and taking audio recordings of each side of the RSS over three passes. The microphones discussed in Section 2.1A were used for this set of measurements. For the first two passes, the microphones were positioned opposite from each other at a distance of thirty inches from the edge of the RSS, and at a height of twelve inches above the grid floor of the chamber. For the third pass, one microphone was positioned at a distance of thirty inches above the center of the RSS. This measurement technique differs from the procedure stipulated in ANSI S12.55 in several significant ways, most notably among these is the inability to analyze several microphone positions concurrently, and the aforementioned limitations of the anechoic chamber [40].

Field PWL measurements were accomplished by positioning the RSS in various outdoor locations, including a residential driveway, an elementary school basketball court, and a collegiate soccer field. The two-surface method was used for each field measurement.

Measurement results for average one-third-octave-band field PWL measurements, average anechoic chamber PWL measurements, the “Field Delta” – or difference in decibels between the maximum and minimum PWL values calculated from field measurements, and the anticipated spectrum for the RSS, referencing the spectrum shown in Figure 2-4, as well as broadband metrics in terms of unweighted, A-weighted, C-weighted, and SQI, are shown graphically in Figure 2-7, and tabulated in Table 2-2.

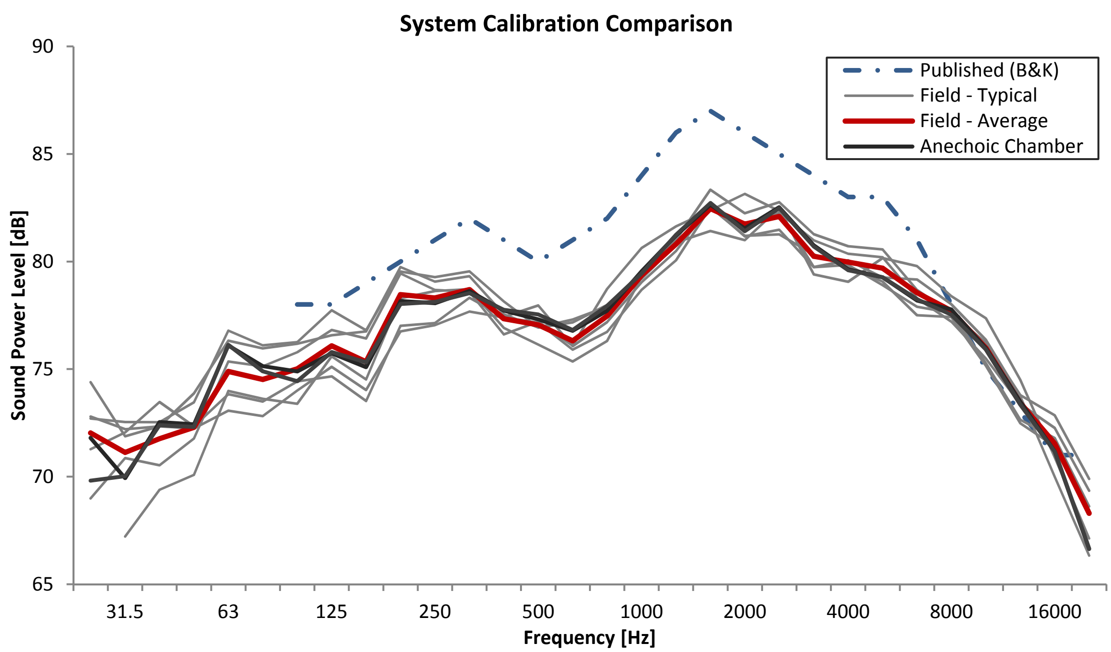

Figure 2-7: Difference in response between the two measurement microphones

Table 2-2: PWL (dB ref. 1pW) Measurement System Calibration Data

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
Field Avg	72.0	71.1	71.8	72.3	74.9	74.5	75.0	76.1	75.3	78.5
Chamber	70.8	70.0	72.5	72.4	76.1	75.0	74.7	75.8	75.2	78.1
Field Delta	5.4	5.3	4.1	3.8	3.7	3.3	2.9	3.1	3.3	3.0
Published	--	--	--	--	--	--	78	78	79	80
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
Field Avg	78.3	78.7	77.3	77.1	76.3	77.5	79.4	80.8	82.5	81.7
Chamber	78.1	78.6	77.7	77.4	76.8	77.8	79.5	81.2	82.7	81.5
Field Delta	2.2	1.9	1.5	1.8	2.0	2.4	1.9	1.6	1.9	2.2
Published	81	82	81	80	81	82	84	86	87	86
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
Field Avg	82.1	80.2	80.0	79.7	78.6	77.7	76.0	73.4	71.5	68.3
Chamber	82.5	80.7	79.6	79.3	78.2	77.7	75.9	73.4	71.2	66.6
Field Delta	1.5	1.9	1.6	1.7	2.3	1.2	2.2	2.0	2.9	3.6
Published	85	84	83	83	81	78	75	73	71	71
	dB	**dBA**	**dBC**	**SQI**	**Definition**					
Field Avg	92.4	91.8	91.9	23.6	Average of 6 field msmnts at 3 locations					
Chamber	92.6	91.9	92.2	23.7	Average of 2 laboratory measurements					
Field Delta	1.3	1.0	1.3	0.7	Difference between max & min field msmnts					
Published	95.9	95.6	95.5	24.4	Interpolated from Figure 2-4 [38]					

The measured values from the field and chamber agree reasonably well with each other, with a maximum deviation of ±2 dB in the one-third-octave-bands above 50 Hz. There is also general agreement between the averaged field measurements and the average chamber measurements – although there are certainly outliers in individual one-third-octave-bands, and similar agreement in the broadband metrics, including SQI.

It is interesting to note that the general shape of the field- and laboratory-measured spectra and the published spectrum are similar, exhibiting a roll-off of approximately 3 dB per octave below the 315 Hz one-third-octave-band, peaks at the 315 Hz and 1,600 Hz one-third-octave bands, and a roll-off of approximately 4 dB per octave between the 1,600 Hz and 8,000 Hz one-third-octave bands, which increases to a slope of approximately 7 dB per octave above the 8,000 Hz one-third-octave bands. However, there was a significant discrepancy between the measured and published PWL values – a discrepancy of up to approximately 5 dB in mid-range one-third-octave bands.

Literature available from the RSS manufacturer [38] indicates that the PWL spectrum produced by the RSS in the field may differ from the published spectrum due to variability in the supplied electrical voltage and frequency, as well as differences in ambient temperature or pressure, although it should be noted that the measurements of taken at four different locations over a period of two months were remarkably consistent. The manufacturer literature also recommends having the RSS recalibrated every 24 months, at a minimum. The date of the most recent RSS calibration was unable to be determined, but it seems probable that the RSS was significantly overdue for recalibration at the time that the measurements were taken, and that this lapse in calibration is the reason that the measured spectra show such a deviation from the published data. In addition to the RSS being out of calibration, it was operated in a fully anechoic space, hence the sound pressure level was reduced compared to the calibration level, which was determined in a hemi-anechoic environment.

2.4: SITE VISIT PROCEDURES

A set of site visit procedures was developed in order to ensure that all of the necessary data points were recorded, and that the site visits were conducted as uniformly and efficiently as possible. Before any audio recordings were made, the screw chiller of interest, and any other significant noise sources were identified, and site conditions were recorded on the Site Data Sheets (shown in Appendix A). A calibration recording was then taken for each microphone, followed by two-surface recordings were taken of as many sides of the screw chiller as were accessible. After the recordings were complete, and in most cases off-site, the recordings were analyzed by the custom-designed software described in Appendix B.

2.4A: Identification of Equipment

The first step in gathering measurements consisted of identifying the equipment to be measured, and any nearby noise sources that may affect measurements, as well as the distance between the extraneous noise sources, or any walls or other significant barriers, and the equipment to be measured. The physical dimensions of the chiller were measured, taking note of the dimensions of any inaccessible portions, and the operating parameters of the chiller, including RPM, fluid flow rates and temperatures, and operating point as a percentage of total capacity, as available. All of this information was recorded on the Site Data Sheet, and photographs were taken of the equipment in-situ from several angles, including of the plate on each unit which was stamped with the unit's model number, the capacity of each compressor, and other information particular to that installation.

Site conditions, including the ambient temperature, wind-speed and direction, were also measured before and after the SPL measurements, and representative values were recorded on the Side Data Sheet, as required by ASTM E1780-12 [36]. SPL measurements were not taken if the wind speed was measured to be greater than 2.0m/s (394 fpm). The SPL at the site was also measured on a calibrated handheld sound level meter (Ivie model IE-35 with ¼-inch random-incidence microphone element – a Type-II device), as a "sanity check" to compare with the two-surface measurements.

2.4B: Two-Surface Measurements

Microphone separation distances were experimented with to find settings that met the minimum 'd1' dimension (refer to Figure 2-2), and maximized the 'd2' dimension, while still being able to fit the measurement apparatus horizontally between the screw chiller and adjacent equipment or structure. Microphone preamplifier gain settings were adjusted to ensure maximum signal-to-noise ratio on the recordings, without any digital clipping of the audio signal. If, after the recordings were complete, digital clipping was found in the audio signal, all affected recordings were retaken.

Once the preamplifier gain settings were established, a 30 second recording of the 1 kHz, 94 dB SPL, calibration signal was recorded for each microphone. Audio recordings were then made, as the microphone was maneuvered over the surface area of each accessible side of the screw chiller, separately. The microphone boom apparatus was maneuvered slowly and evenly in a sweeping motion, as prescribed in ASTM E1124 [25], and as depicted in Figure 2-8.

In order for the data analysis application to associate the audio recordings with the correct microphone, all audio from the inner surface microphone was recorded to odd-numbered channels (calibration tone on channel 1, and audio from up to five sides of the equipment on channels 3, 5, 7, 9, and 11), and all audio from the outer surface microphone was recorded to even-numbered channels (calibration tone on channel 2, and audio from up to five sides of the equipment on channels 4, 6, 8, 10, and 12).

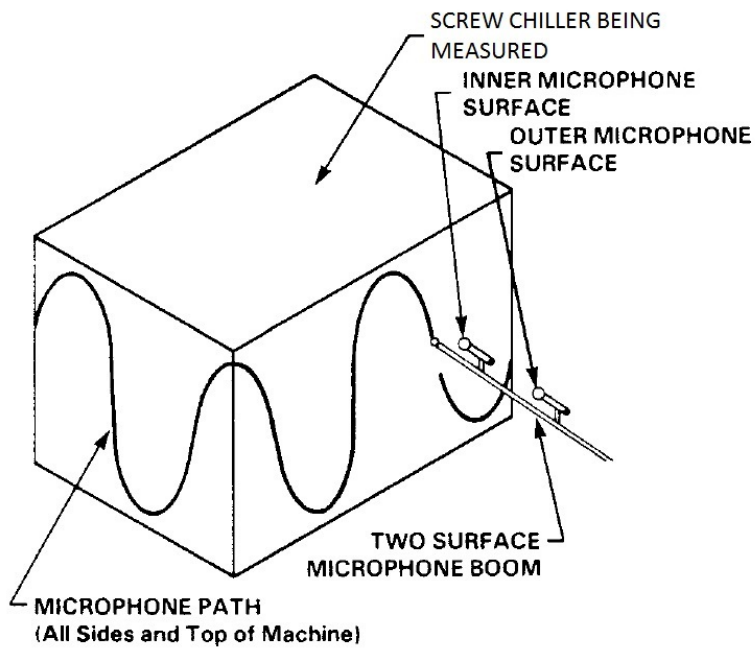

Figure 2-8: Measurement Diagram. Adapted from ASTM E1124 [25]

2.4C: Post-Processing and Data Analysis

Once off-site, the recordings were listened to, to ensure that there was no wind noise or other artifacts that would affect the PWL calculation. Each pair of recordings was then saved as uncompressed stereo WAV files (44.1kHz sampling frequency, 16 bit-depth), with the inner microphone signal in the left channel, and the outer microphone signal in the right channel.

The stereo WAV files were loaded into the custom audio processing interface, PWL was calculated within the custom interface on one-third-octave-band, octave-band

and broadband bases, and the data was exported to a spreadsheet for further analysis. The operation of the audio recording software, the custom processing interface and the exported spreadsheet are covered in greater detail in Appendix B.

2.5: COMPROMISES & LIMITATIONS

In all cases, the top surface was inaccessible; side surfaces, or portions of side surfaces, were inaccessible at various other sites. The inaccessible side surfaces were limited in number, and in all cases where a side surface was completely inaccessible, the opposite side of the unit, which had similar dimensions and sound production characteristics, was accessible; the measurement from the accessible side was used in lieu of the unobtainable measurement. This is a reasonable approach because the measurements taken at opposite sides of a given chiller, when both sides were accessible, exhibited remarkably similar SPL spectra. In fact, it is common practice in the industry for manufacturers to quote screw chiller generated sound data for a long side, a short side and the top, with the implicit assumption that both long sides and both short sides produce noise at equivalent levels.

Inaccessible portions of side surfaces were accounted for using the methodology prescribed in ASTM 1124 [25], and covered here in Equation (1.16). The inaccessibility of the top of all of the screw chillers was assumed to be a much more significant omission, as the tops of the units, particularly air-cooled units, often include other noise sources, such as axial fans, which are likely not fully apparent in the measurements taken at the side surfaces. The lack of measured data from the tops of the units was accounted for by taking the SPL measurements from the long sides a given chiller, and applying them to the surface area of the top of the unit. This gives a conservative estimate of the PWL radiated off the top surface because the long sides were invariably the noisier sides of the screw chillers, however, the axial fans were not accounted for in this analysis because in most cases the number of fan blades and rotational velocity of the fans was unknown; if these variable had been known, an even more conservative estimate could be obtained by using the empirical correlation for axial fans published by Laymon Miller [4], and logarithmically combining the calculated effect of the fans with the SPL measurements from the long side, applied with the surface area of the top of the unit.

The equipment available included only Type II microphones, with ¼” elements, and “prosumer” audio equipment. This, combined with the aforementioned anechoic chamber low-frequency limit of around 125 Hz, and modal anomalies within the measurement environments, are likely the cause of the wildly varying low-frequency readings, and for the frequency bands for which no valid calculation could be made. It is likely that a PWL measurement technique based on sound intensity levels (SIL) would produce more uniform low-frequency results. The fact that SIL measurements contain vector information allows contributions of noise sources outside of the measurement surface to be cancelled out. However, the equipment required for SIL field measurements was not available.

It is not clear when the last calibration of the RSS was performed. This may have an effect on the magnitude of the resulting PWL values, but does not seem to affect the shape of the spectrum.

Chapter 3: Measurement Site Descriptions[3]

A total of eleven screw chillers were visited, and each chiller was measured between one and three times at different operation conditions for a total of twenty measurements. The measurements are summarized in Table 3-1. In this table, each measurement is assigned a sequential number and an alphanumeric identification tag. The sequential number corresponds to the order in which the measurements were taken. The number in the alphanumeric ID tag indicates the specific chiller unit, and the letter in the ID tag indicates the operating condition for that chiller unit; the alphanumeric ID is indicated in the top-right corner of each of the Site Data Sheets shown in Appendix A. The type of screw chiller (air- or water-cooled) is indicated, as is the total cooling capacity, the operating condition as a percentage of the total cooling capacity, the A-weighted PWL, and the SQI.

The calculated one-third-octave-band PWL values for each measurement are tabulated and shown graphically in Appendix A, alongside the Site Data Sheet for the same measurement. Calculated octave-band PWL values for each measurement are also shown in Table A-21, in Appendix A. The individual chillers and measurement sites used for this research are discussed in this chapter.

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[3] The work in this chapter was part of the basis for a paper presented at Noise-Con 2017, which Daniel Alon Hemme was the primary author of, with co-authors David A. Nelson, and Preston S. Wilson.

Characterization of Sound Power Level Spectra Produced by HVAC Chillers with Double Helical Rotary Screw Compressors Under Various Operating Conditions. **Hemme, Daniel A, et al.** Grand Rapids, MI: Noise-Con 2017.

Table 3-1: Summary of screw chillers measurements. A-weighted PWL values are ref. 1 pW.

#	ID	Chiller Type	Cap. [tons]	%	PWL [dBA]	SQI
1	1A	Water-Cooled	106	25	97.5	25.1
14	1B	Water-Cooled	106	65	102.5	27.1
2	2A	Air-Cooled	247	35	99.7	26.1
17	2B	Air-Cooled	247	53	101.1	26.5
3	3A	Air-Cooled	157	31	97.3	25.2
12	3B	Air-Cooled	157	50	100.1	26.0
4	4A	Air-Cooled	153	31	98.8	25.7
5	5	Air-Cooled	163	31	101.6	27.0
15	4B	Air-Cooled	153	68	98.4	25.7
16	6	Air-Cooled	163	70	101.2	26.6
6	7A	Air-Cooled	80	52	89.3	22.6
11	7B	Air-Cooled	80	72	89.9	22.8
7	8A	Water-Cooled	248	77	98.4	26.8
13	8B	Water-Cooled	248	91	101.8	27.9
8	9A	Water-Cooled	170	72	103.3	26.8
9	9B	Water-Cooled	170	46	115.7	31.6
10	10A	Water-Cooled	170	61	108.5	28.2
18	9C	Water-Cooled	170	72	105.6	27.3
19	11	Water-Cooled	170	69	106.8	27.8
20	10B	Water-Cooled	170	68	105.2	27.2

3.1: Screw Chiller #1

Screw chiller #1 is a 106 ton water-cooled unit, manufactured by Carrier, and installed in an enclosed Mechanical Room at an elementary school. This unit was visited twice, once in the spring, and once in the summer. A photograph of screw chiller #1 is shown in Figure 3-1.

Figure 3-1: Photograph of Screw Chiller #1

The equipment room contained various other equipment including pumps associated with the chiller itself, and exhaust/ ventilation fans. There were pipes and electrical panels that prevented access to some portions of the chiller. Both of the long sides and just over half of one of the short sides were accessible for measurement.

3.2: SCREW CHILLER #2

Screw chiller #2 is a 247 ton air-cooled unit, manufactured by York/ Johnson Controls, and installed outdoors on the roof deck of a four-story medical office building. This unit was visited twice, once in the spring, and once in the summer. A photograph of screw chiller #2 is shown in Figure 3-2.

Figure 3-2: Photograph of Screw Chiller #2

The chiller was the only significant noise source on the rooftop. There were some exhaust fans, but they were not producing noise at an appreciable level. All four vertical surfaces of this chiller were accessible for measurement; however, the fact that the chiller was installed on an elevated frame presented a difficulty in taking measurements with the boom apparatus normal to the chiller over the entire measurement surface.

3.3: SCREW CHILLER #3

Screw chiller #3 is a 157 ton air-cooled unit, manufactured by York/ Johnson Controls, and installed in an outdoor chiller yard, adjacent to an office building. This unit was visited twice, once in the spring, and once in the summer. A photograph of screw chiller #3 is shown in Figure 3-3.

Figure 3-3: Photograph of Screw Chiller #3

The chiller was the only significant noise source in the equipment yard. There was a generator and some pumps, but the generator was not in operation, and the pumps were located in a pit, approximately fifteen feet below the chiller, and did not seem to be in operation. All four vertical surfaces of this chiller were accessible for measurement.

3.4: SCREW CHILLER #4

Screw Chiller #4 is a 153 ton air-cooled unit, manufactured by Carrier, and installed in an outdoor chiller yard on the top deck of a parking structure. This unit was visited twice, once in the spring, and once in the summer. A photograph of screw chiller #4 is shown in Figure 3-4.

Figure 3-4: Photograph of Screw Chiller #4

There was an additional screw chiller active in the equipment yard during both of the site visits, in addition to some pumps and associated piping.. All four vertical surfaces of this chiller were accessible for measurement.

3.5: Screw Chiller #5

Screw Chiller #5 is a 163 Ton air-cooled unit, manufactured by Carrier, and installed in the same outdoor chiller yard as Screw Chiller #4. This unit was only available at the spring site visit. A photograph of screw chiller #5 is shown in Figure 3-5.

There was an additional screw chiller active in the equipment yard at the time that Screw Chiller #5 was measured. All four vertical surfaces of this chiller were accessible for measurement.

Figure 3-5: Photograph of Screw Chiller #5

3.6: SCREW CHILLER #6

Screw Chiller #6 is a 163 yon air-cooled unit, manufactured by Carrier. This unit is identical to Screw Chiller #5, and is installed in the same outdoor chiller yard as Screw Chillers #4 & #5. This unit was only available at the summer site visit.

There was an additional screw chiller active in the equipment yard at the time that Screw Chiller #6 was measured. All four vertical surfaces of this chiller were accessible for measurement.

3.7: SCREW CHILLER #7

Screw Chiller #7 is an 80 ton air-cooled unit, manufactured by Trane, and installed in an outdoor chiller yard located outside a community center. This unit was visited twice, once in the spring, and once in the summer. A photograph of Screw Chiller #7 is shown in Figure 3-6.

Figure 3-6: Photograph of Screw Chiller #7

There were no other significant noise sources active in the equipment yard at the time that Screw Chiller #7 was measured. All four vertical surfaces of this chiller were accessible for measurement.

This unit, located in relatively close proximity to a high-rise condominium and public parkland, is the only screw chiller in this study for which significant noise control measures were installed. This unit was equipped with a shroud around the bank of axial fans at the top of the unit, as well as custom-fitted mass loaded blankets around the screw compressors themselves. The fan shroud is visible in Figure 3-6, and a detail of the noise control blankets on the screw compressor is shown in Figure 3-7.

Figure 3-7: Compressor Blankets on Screw Chiller #7

3.8: SCREW CHILLER #8

Screw Chiller #8 is a 248 ton water-cooled unit, manufactured by York, and installed in an enclosed mechanical room at a community college. This unit was visited twice, once in the spring, and once in the summer.

This screw chiller is installed in an equipment room along with two other similar sized units. Neither of the other units was in operation during either site visit. Other noise sources in the equipment room include pumps associated with the screw chillers. Three sides of Screw Chiller #8 were available for measurement.

Figure 3-8: Photograph of Screw Chiller #8

3.9: SCREW CHILLER #9

Screw Chiller #9 is a 170 ton water-cooled unit, manufactured by Trane, and installed in an enclosed mechanical room at a high school. This unit was visited twice, once in the spring, and once in the summer. The technician who provided access to this chiller was able to force the unit into a second operating condition during the spring visit, for a total of three operating condition measurements for Screw Chiller #9.

This screw chiller is installed in an equipment room along with two other similar sized units. Neither of the other units were in operation during the spring site visit, but one (Screw Chiller #11) was in operation during the summer site visit. Other noise sources in the equipment room include pumps associated with the screw chillers. Three sides of Screw Chiller #9 were available for measurement.

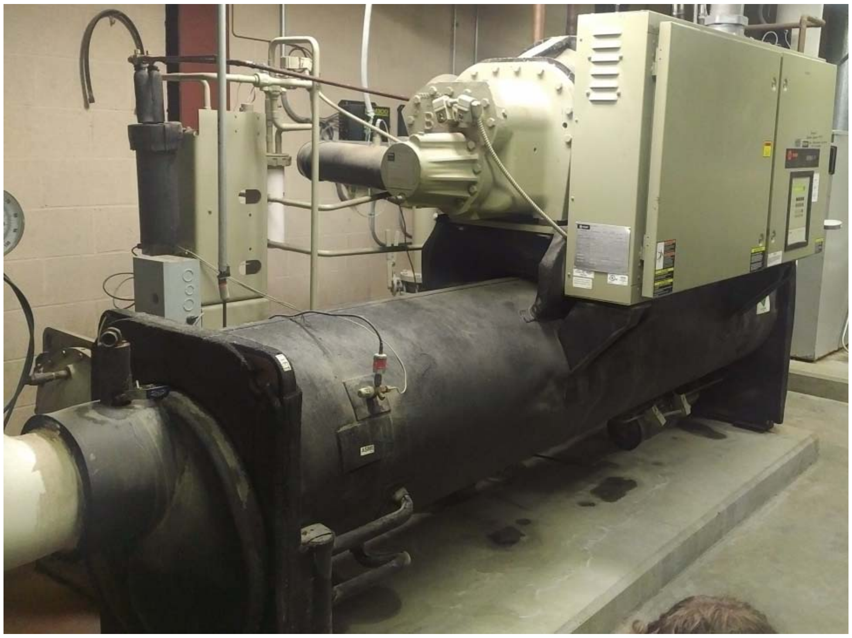

Figure 3-9: Photograph of Screw Chiller #9

3.10: Screw Chiller #10

Screw Chiller #10 is a 170 ton water-cooled unit, identical to Screw Chiller #9, and installed in a separate enclosed mechanical room at the same high school. This unit was visited twice, once in the spring, and once in the summer.

This screw chiller is installed in an equipment room along with other noise sources, including pumps associated with the screw chillers. Three sides of Screw Chiller #10 were available for measurement.

3.11: Screw Chiller #11

Screw Chiller #11 is a 170 ton water-cooled unit. This unit is identical to Screw Chillers #9 and #10, and is installed in the same mechanical room as Screw Chiller #9. This unit was only available at the summer site visit.

This screw chiller is installed in an equipment room along with other noise sources, including pumps associated with the screw chillers. Three sides of Screw Chiller #11 were available for measurement.

Chapter 4: Analysis & Discussion

Sound data for the air- and water-cooled screw chillers was analyzed separately on a one-third-octave-band basis, as well as in terms of SQI ratings. Measurements from both types of chillers were also compared, on an octave-band basis, with the spectrum for screw chiller PWL published by Laymon Miller [4]. The one-third-octave-band analysis included comparrison on the basis of the units' total cooling capacities, and the operating points expressed as a percentage of the total cooling capcity, both as compared to smoothed averages of each chiller type. The smoothed averages were used as a baseline spectrum, excluding the effect of the prominent narrow-band components, on which the work towards parameterized empirical correlations were based.

The smoothed average was calculated by averaging each one-third-octave-band PWL value between 31.5 Hz and 16 kHz with the two adjacent bands, and then averaging the smoothed spectra.

The smoothed average for each one-third-octave-band spectrum of each measurement was calculated as follows:

$$L_{i*} = \frac{L_{i-1}+L_i+L_{i+1}}{3} \qquad (4.1),$$

where: L_{i*} [dB] ≡ the smoothed PWL for the *i*th one-third-octave-band,

$L_{\#}$ [dB] ≡ the measured PWL for the specified one-third-octave-band, where # is noted as i, $i-1$, or $i+1$,

i ≡ one-third-octave-bands with center frequencies between 31.5 Hz and 16 kHz, and

$i-1$ and $i+1$ ≡ one-third-octave-bands immediatelay below and above the *i*th one-third-octave-band, respectively.

Once the smoothed average spectrum for each measurement was determined, the smoothed average for each type of screw chiller was calculated, as follows:

$$L_{i**} = \frac{1}{n}\sum_{j}^{n} L_{i*,j} \qquad (4.2),$$

where: L_{i**} [dB] ≡ the smoothed average PWL for the ith one-third-octave-band,

$L_{i*,j}$ [dB] ≡ the smoothed PWL for the ith one-third-octave-band of measurement j, as calculated in Equation (4.1),

j ≡ counter indicating the measurement number being considered, and

n ≡ the total number of measurements for the chiller type being considered.

Notable outliers in the data sets for both types of screw chillers were excluded from this analyisis; this is discussed in greater detail in the following sections.

The smoothed average was used in the development of the empirical correlations, as will be discussed later in this chapter. Once the correlations were developed, the coefficient of determination, or R-squared coefficient, of each calculated spectrum with respect to the corresponding measured spectrum was calculated. The R-squared coefficient is the output of a form of regression analysis which, put simply, gives an idea of how well two curves being analyzed correlate. The value of the coefficient ranges between 0.0 and 1.0, indicating no correlation and perfect correlation, respectively. The R-squared coefficient is calculated as follows:

$$R^2 = \left(\frac{n(\sum_i^n MC) - (\sum_i^n M)(\sum_i^n C)}{\sqrt{[n(\sum_i^n M^2) - (\sum_i^n M)^2][n(\sum_i^n C^2) - (\sum_i^n C)^2]}}\right)^2 \qquad (4.3)$$

where: n ≡ the total number of one-third-octave-bands being considered for the regression analysis,

i ≡ a counter indicating the one-third-octave-band being considered,

M ≡ PWL values of the measured spectrum, and

$C \equiv$ PWL values of the calculated spectrum.

It is worth noting that in all but one case, the equipment operator was unable to tell what the rotational velocity of the driven rotor of the screw compressor was. In all cases, the rotational velocity used in the development of the empirical formula was calculated based on Equation (1.1), and information on the compressors sourced from manufacturer's literature, or the manufacturer's sales representatives. In the case of Screw Chiller #1, the only unit for which a rotational velocity was available on site, the reported rotational velocity, 3,500 RPM at both visits, along with the 5 lobes on the male rotor, agrees well with the peak in the 400 Hz one-third-octave-band; the more significant peak in the 800 Hz one-third-octave-band is likely a harmonic of the lower-frequency peak. The fact that the harmonic frequency exhibited a higher peak that the fundamental frequency seemed to be the case with water-cooled chillers, but not with air-cooled units.

It should also be noted that the data set available for analysis had a fairly narrow range of cooling capacity and operating range for both types of screw chillers. The air-cooled screw chiller cooling capacities ranged between 80 tons and 247 tons, operating between 31% and 72%; the ranges for the units used in the development of the empirical correlation were even narrowerer: capacities between 153 tons and 247 tons, and operating points between 31% and 70%. The water-cooled screw chiller cooling capacities ranged between 106 tons and 248 tons, operating between 25% and 91%.

4.1: Air-Cooled Screw Chiller Comparison

A total of six air-cooled screw chillers were measured for this project. All but two were available for measurement under two operating conditions, for a total of ten PWL measurements of air cooled chillers.

4.1A: Air-Cooled Chiller One-Third-Octave-Band Comparison

The one-third-octave-band PWL measurements of air-cooled screw chillers are shown in Figure 4-1, along with the smoothed average of the air-cooled chiller measurements, calculated according to Equations (4.1) and (4.2).

One air-cooled unit, Screw Chiller #7, has noise control equipment installed, including mass-loaded blankets on the compressors and a shrowd around the axial fans at the top of the unit. The sound levels produced by this unit were significantly lower than sound levels produced by other air-cooled screw chillers that were measured. These measurements are not considered in the development of the baseline spectrum for air-cooled chillers. The spectra measured for this unit are indicated with an asterisk in Figure 4-1. The values of the baseline spectrum are tabulated in Table 4-1.

A general trend is observed in the mean spectrum for air-cooled screw chillers, as follows: PWL increasing approximately 3 dB per octave up to the 250 Hz one-third-octave-band, and decreasing approximately 5 dB per octave above this point.

Table 4-1: Smoothed Mean PWL Spectrum for the Air-Cooled Screw Chiller Empirical Formula

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB ref. 1 pW]	83.6	84.5	85.4	86.8	88.0	86.4	85.9	86.9	88.3	91.2
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB ref. 1 pW]	91.9	92.3	91.1	91.3	91.8	91.5	89.9	89.1	87.4	85.8
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB ref. 1 pW]	82.9	79.9	77.6	76.2	77.0	76.3	73.9	69.4	65.9	62.5

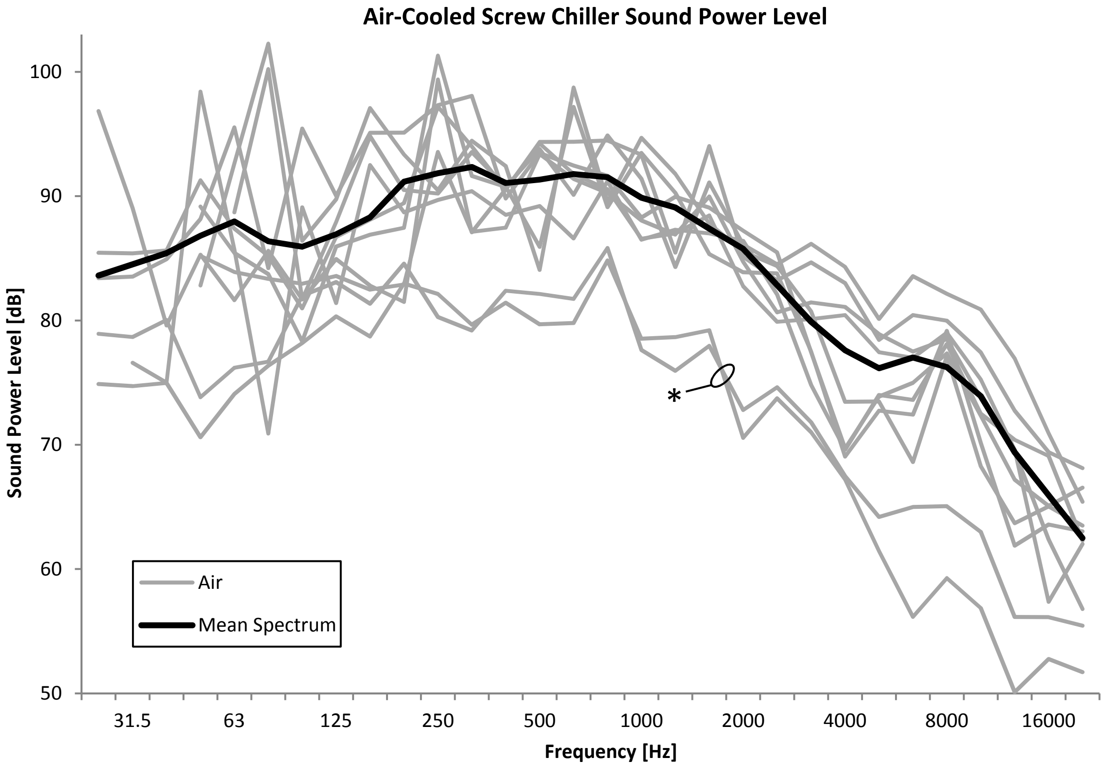

Figure 4-1: Comparisson of air-cooled chiller one-third-octave-band PWL spectra (ref. 1 pW), along with a calculated mean spectrum. The two spectra indicated with an astrisk (*) are for the only unit measured that had noise control equipment installed; these measurements were not considered in the development of the mean spectrum.

The measurements were analyzed on the basis of the total cooling capacity of the units, which ranged between 153 and 247 tons; the total cooling capacity of Screw Chiller #7, which was not considered in the development of the empirical correlation, was 80 tons. The measured spectra are shown, grouped as follows: Screw Chiller #4, the 153 ton unit in Figure 4-2; Screw Chiller #3, the 157 ton unit in Figure 4-3; Screw Chiller #5, the 163 ton unit in Figure 4-4; and Screw Chiller #2, the 247 ton unit, along with Screw Chiller #7, the 80 ton unit in Figure 4-5. The spectrum for Screw Chiller #7 is shown for reference only; these spectra are marked with an asterisk, and were not used in the development of the empirical correlation. The mean spectrum is shown for reference in each chart.

The magnitudes of the spectra for the 153 ton, 157 ton, and 163 ton units show a slight positive correlation with the total cooling capacity. This is particularly the case for mid-band frequencies between the 100 Hz and 5,000 Hz one-third-octave-bands. Within this frequency range, the average deviation from the mean spectrum for 153 ton units, 157 ton, and 163 ton units is -1.3 dB, -0.3 dB, and 1.2 dB, respectively. This correlation is not seen with the 247 ton unit, for which the average deviation from the mean spectrum within the stated mid-band frequency range is 0.1 dB. The positive correlation is not linear with respect to the screw chiller capacity. Note that in this comparison, a negative deviation indicates that the mean spectrum is generally above the measured spectra, and a positive deviation indicates that the measured spectra are generally above the mean spectrum.

The measurements were analyzed on the basis of the operating point, expressed as a percentage of the total chilling capacity. Variation of the operating point was found to have a slight effect on the overall level of the spectra in most cases, and in some cases an effect on the magnitude of the narrow-band component.

Refer to Figure 4-2, showing the spectra measured for the 153 ton unit operating at 31% and 68% of its total capacity. It is shown that the spectra produced by the unit at both operating points track each other quite well, with the notable exception that the peak in the 250 Hz one-third-octave-band is almost 6 dB higher at the lower operating point.

The spectra for the 157 ton unit operating at 31% and 50% of its total capacity, shown in Figure 4-3, shows a different trend. In this case, the unit is louder in nearly all one-third-octave-bands when at the higher operating point - by an average of 3.8 dB over the 100 Hz to 5,000 Hz frequency range.

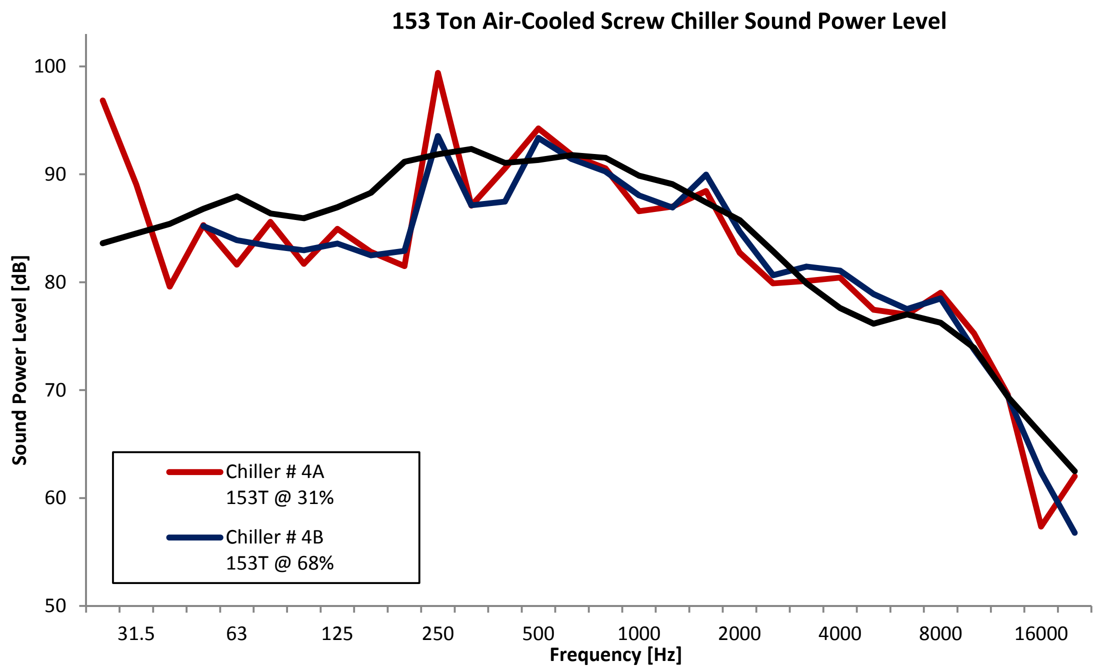

Figure 4-2: Comparisson of air-cooled chiller one-third-octave-band PWL spectra, for units with total cooling capacities of 153 HVAC tons

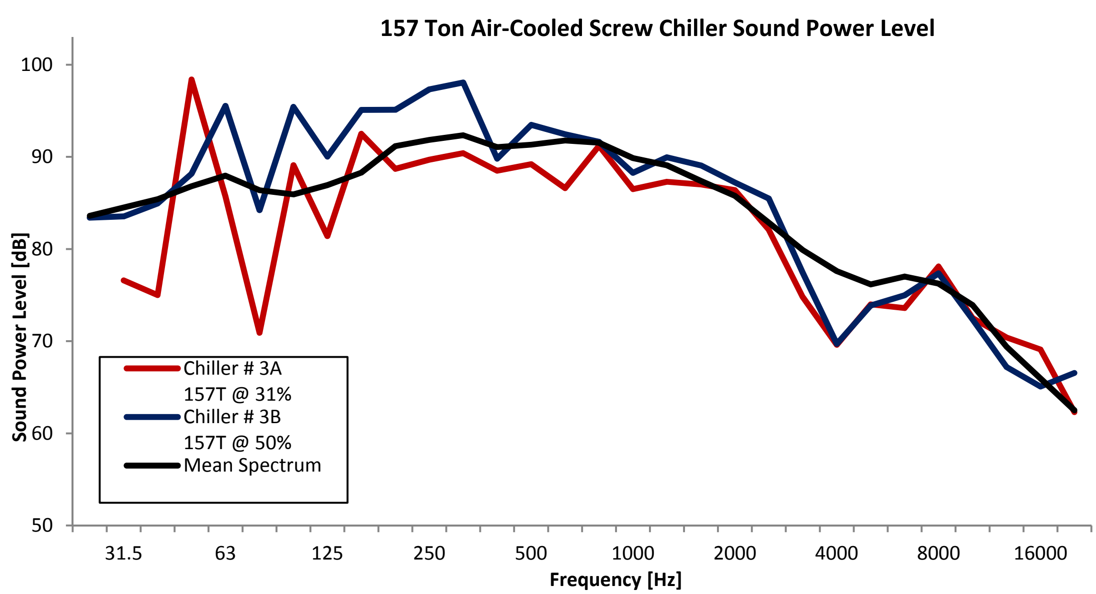

Figure 4-3: Comparisson of air-cooled chiller one-third-octave-band PWL spectra, for units with total cooling capacities of 157 HVAC tons

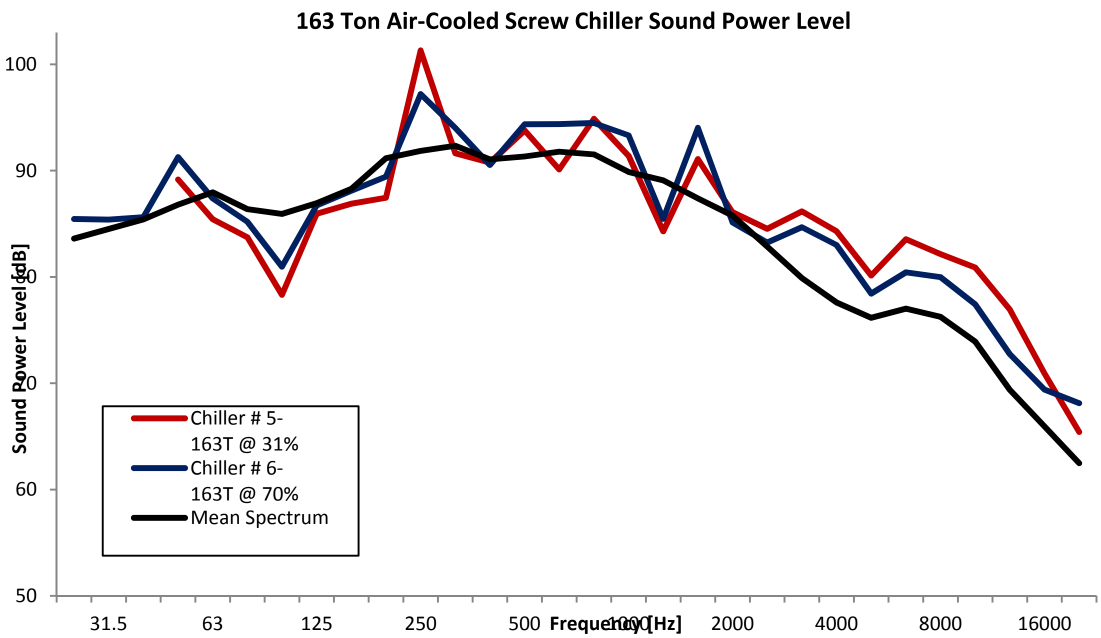

Figure 4-4: Comparisson of air-cooled chiller one-third-octave-band PWL spectra, for units with total cooling capacities of 163 HVAC tons

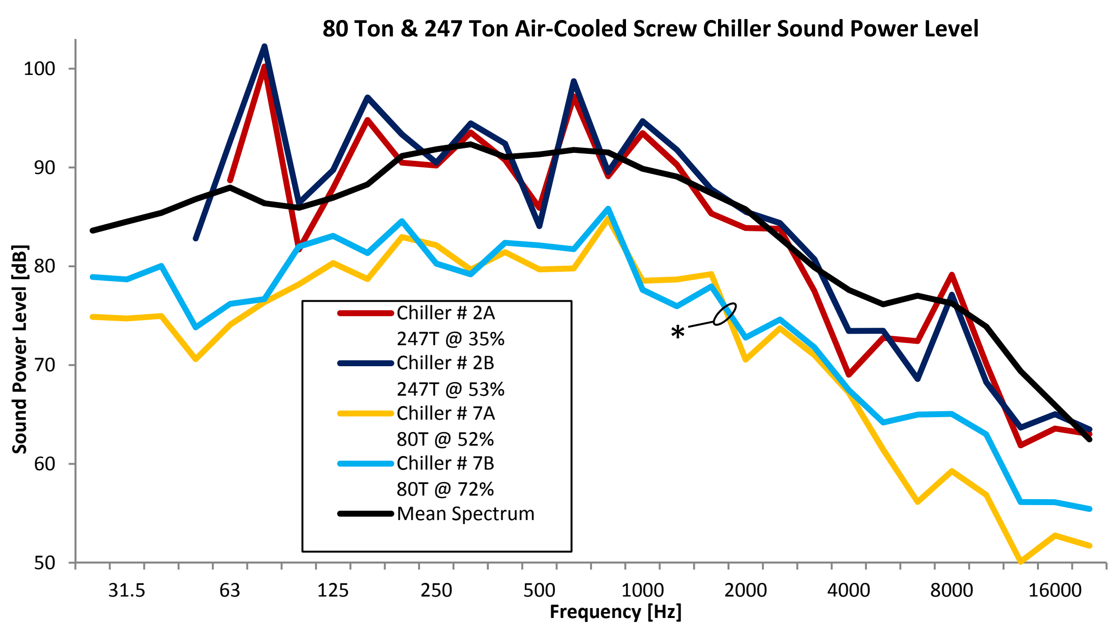

Figure 4-5: Comparisson of air-cooled chiller one-third-octave-band PWL spectra, for units with total cooling capacities of 80 and 247 HVAC tons

The spectra for the 163 ton unit operating at 31% and 70% of its total capacity is shown in Figure 4-4. The unit is shown to be louder at higher frequencies, above the 2,000 Hz one-third-octave-band, when at the lower operating point, and generally louder when at the higher operating point below this frequency, with the notable exception of the narrow-band component within the 250 Hz one-third-octave-band, which is 4.1 dB higher at the lower operating point versus the higher.

The spectra for the 247 ton unit operating at 35% and 53% of its total capacity, shown in Figure 4-5, display a similar trend to the 157 ton unit. The unit is an average of 1.9 dB louder over the 100 Hz to 5,000 Hz frequency range when at the higher operating point, as compared to the lower operating point.

In general, it is shown that the overall sound levels produced by air-cooled screw chillers increases with total cooling capacity, and with the operating point, although the magnitude of the narrow band component can, in some cases, increase when at a lower operating point.

4.1B: Air-Cooled Chiller Empirical Correlation

The form of the empirical correlation is similar to many of the correlations developed by Laymon Miller [4], in that the variables used are quantities that the mechanical engineer designing the system in which the screw chiller will be a part of would know, or at least be able to estimate. These variables include the total cooling capacity of the chiller, the operating point, expressed as a percentage of the total capacity, the rotational velocity of the driven rotor, and the number of lobes on the driven rotor. Beyond these variables, there is a constant baseline spectrum, which is developed from the mean spectrum. The baseline spectrum is shown in Table 4-2. The form of the empirical correlation for PWL generated by air-cooled screw chillers is shown in Equation (4.3).

$$\mathrm{PWL} = (M - m) + c\log(C) + pP + K_{NB} \qquad (4.3),$$

where: M [dB] ≡ baseline one-third-octave-band PWL, as shown in Table 4-1,

m [dB] ≡ deviation from baseline one-third-octave-band PWL,

c [dB] ≡ penalty due to chiller cooling capacity,

C [tons] ≡ chiller cooling capacity,

p [dB] ≡ penalty due to operating point,

P [%] ≡ chiller operating point, and

K_{NB} ≡ narrow-band correction term, to be included only for the one-third-octave-band containing the LPF, which acan be calculated as per Equation (1.1).

The dependence of the overall PWL on the capacity of the air-cooled chillers was explored, based on A-weighted and C-weighted averages this dependence is shown graphically in the left panel of Figure 4-6. The dependence of the overall PWL on the operating point was similarly explored, and is shown graphically in the right panel of Figure 4-6. Linear lines-of-best-fit are shown, although with a larger dataset available, it would likely make sense to use a logarithmic line-of-best-fit for the capacity comparison, since the higher-capacity chillers are generally louder than lower-capacity units, but this is less pronounced at higher capacities. Similarly, with a larger dataset available, it may make sense to use a polynomial line-of-best-fit for the operating point comparison, as the loudest units for a given size seem to be operating around 80% of their total capacity.

The variables m, c and p were developed by selecting an arbitrary value of each variable, and analyzing the R-squared coefficient based on the measured and modeled curves. The variables were modified in order to find the R-squared coefficient closest to a value of 1.0. The minimum R-squared coefficient, averaged for all of the air-cooled screw chiller measurements (except Screw Chillers #7A and #7B), was found to be 0.727. The minimum R-squared coefficient for air-cooled units was 0.599, for Screw Chiller #5; the maximum was 0.832, for Screw Chiller #2A. The value of m was found to be 3.6761, c was found to be 0.2076, and p was found to be 0.0618. The difference $M - m$ defines the baseline spectrum, *B*.

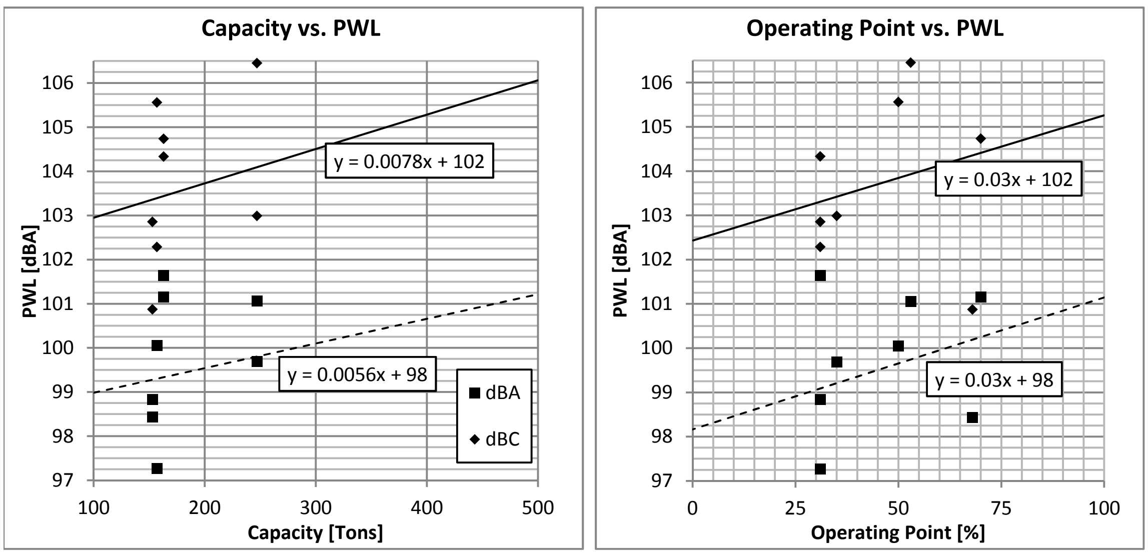

Figure 4-6: Comparisson of A-weighted PWL values versus total cooling capacity (left panel) and operating point (right panel) for air-cooled screw chillers

Table 4-2: Baseline PWL Spectra for the Air-Cooled Screw Chiller Empirical Formula

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB ref. 1 pW]	74.7	75.6	76.5	77.9	79.1	77.5	77.1	78.1	79.4	82.3
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB ref. 1 pW]	83.0	83.5	82.2	82.5	82.9	82.7	81.0	80.2	78.5	76.9
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB ref. 1 pW]	74.0	71.0	68.7	67.3	68.1	67.4	65.0	60.5	57.1	53.6

The variable K_{NB} was developed by analyzing the deviation between the peak PWL value and the mean spectrum with the c and p penalties included. The magnitude of the peak, and also the magnitude of the deviation, was found to vary by cooling capacity and by the operating point in a roughly parabolic relationship, which was simplified to an absolute value relationship, and then weighted. The deviations between the peak level and the empirical correlation versus the cooling capacity and the operating point are shown in Figure 4-7.

The empirical correlation for PWL produced by air-cooled screw chillers, developed in the form presented in Equation (4.3), then can be written as:

$$L_W = B + 0.2076\log(C) + 0.0618P + K_{NB} \qquad (4.4a),$$

$$K_{NB} = [0.85(14 - 0.2|C - 200|) + 0.15(12.5 - 0.3|P - 50|)] \qquad (4.4b)$$

where: B [dB] ≡ baseline one-third-octave-band PWL spectrum per Table 4-1.

Note that K_{NB} is only added to the one-third-octave-band containg the LPF, as calculated by Equation (1.1), and that this variable includes components with the absolute value terms.

4.1C: Air-Cooled Chiller Octave-Band Level Comparison

The octave-band PWL measurements of the air-cooled screw chiller are shown in Figure 4-8, along with the curve for the empirical correlation for screw chiller PWL published by Miller [4], tabulated in Table 4-3. The measured curves for the air-cooled units match the published curve remarkably well, with the notable exception of the 80 ton unit, which was previously noted to be the only unit for which enhanced noise control measures were taken.

A regression analysis was undertaken for the octave-band-level measurements, with respect to the previously published curve, in a similar manner to the analysis for the one-third-octave-band measurements. The average R-squared value for air-cooled units was found to be 0.711, and the minimum and maximum were found to be 0.522 and 0.923, respectively.

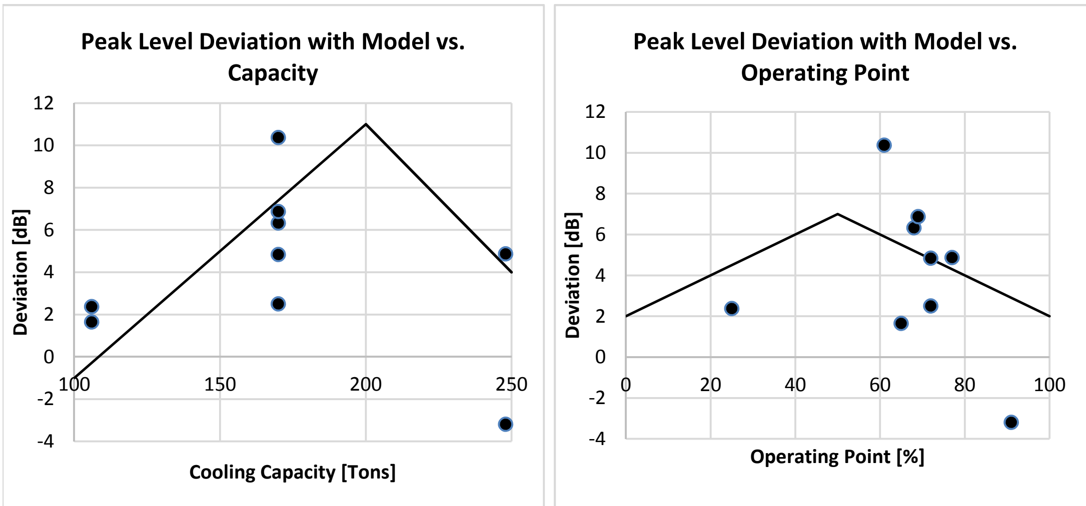

Figure 4-7: Comparisson of LPF level deviation between measured and modeled air-cooled screw chiller PWLs

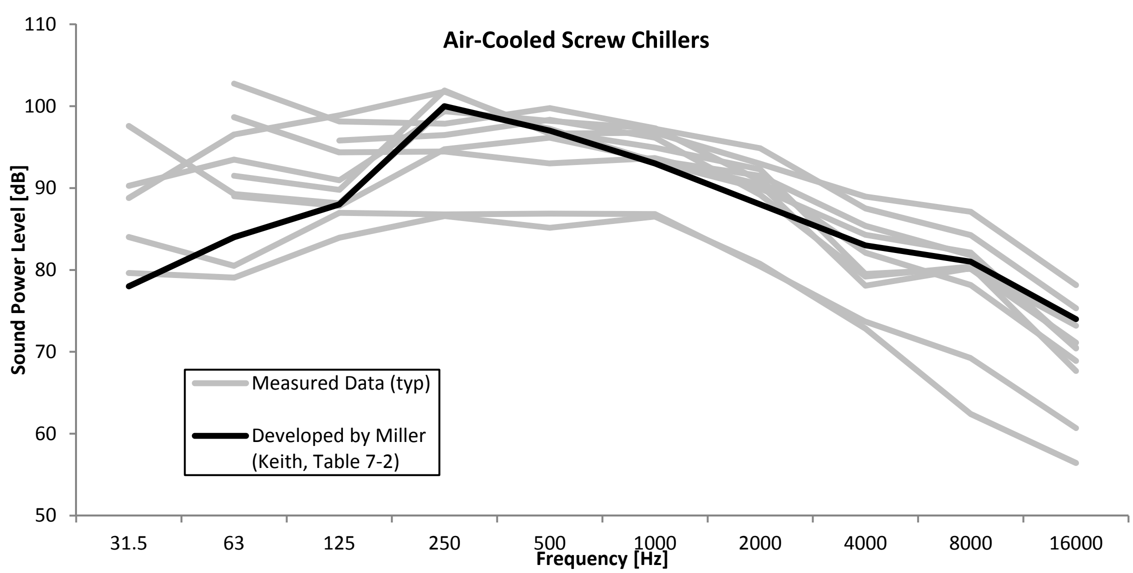

Figure 4-8: Comparisson of air-cooled screw chiller PWL measurements with Miller's published spectrum

The close correlation between the measured curves and the previously published curve lead to the inference that Miller's spectrum was based on measurements taken from air-cooled screw chillers.

Table 4-3: Typical Screw Chiller PWL Spectrum, as published by Laymon Miller [4]

Frequency [Hz]	**31**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
PWL ref. 1pW [dB]	78	84	88	100	97	93	88	83	81

Broadband Metric	**dB**	**dBA**
PWL ref. 1pW [dB]	103	98

4.1D: Air-Cooled Chiller SQI Comparison

The SQI ratings for the air-cooled screw chillers are shown in Figure 4-9, compared against the chiller cooling capacity in the left panel, and agains the operating point in the right panel. These ratings range between 22.6 and 27.0, with an average of 25.4. Note that both the 22.9 and 22.8 SQI ratings are from Screw Chiller #7, which was not used in the development of the empirical formula; the lowest SQI rating for air-cooled units that were considered in the development of the empirical formula was 25.2, and the standard deviation for this reduced data set was 0.54. The SQI ratings for air-cooled chillers are tabulated in Table 4-4; in this table, the chillers are arranged in order of increasing overall cooling capacity and operating point for a given cooling capacity.

In general the SQI ratings are higher for units with higher cooling capacities, with the notable exception of Screw Chillers #2A and #2B, the 247 ton unit, with SQI ratings at 26.1 and 26.5, respectively. Similarly, a given chiller at a higher operating point was found to generally have a higher SQI rating than at a lower operating point, with the notable exception of Screw Chiller #5, operating at 31%, and with an SQI rating of 27.0.

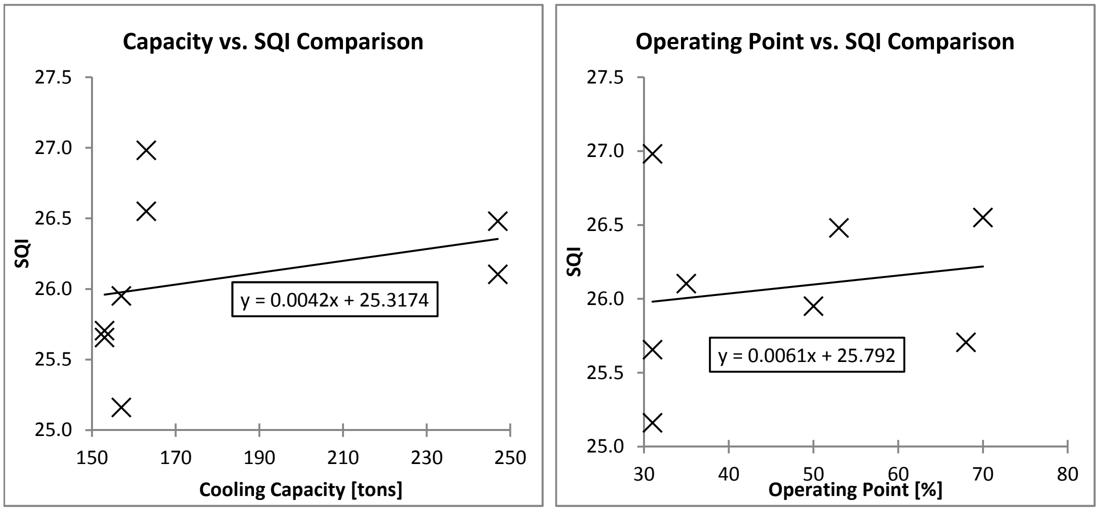

Figure 4-9: Comparisson of air-cooled screw chiller SQI ratings

4.2: WATER-COOLED SCREW CHILLER COMPARISON

A total of five water-cooled screw chillers were measured for this project. Four of the units were available for measurement under two operating conditions, and the operator was able to force one of these units into a third operating condition during one of the site visits. The remaining unit was only available for measurement under a single operating condition, for a total of ten PWL measurements of water cooled chillers.

4.2A: Water-Cooled Chiller One-Third-Octave-Band Comparison

The one-third-octave-band PWL measurements of water-cooled screw chillers are shown in Figure 4-10, along with the smoothed average of the measurements, calculated in the same way that the baseline curve was developed for the air-cooled chillers, as discussed previously.

Table 4-4: Summary of air-cooled screw chiller SQI ratings

ID	Cap. [tons]	Operating Pt. [%]	SQI
7A	80	52	22.6
7B	80	72	22.8
4A	153	31	25.7
4B	153	28	25.7
3A	157	31	25.2
3B	157	50	26.0
5	163	31	27.0
6	163	70	26.6
2A	247	35	26.1
2B	247	53	26.5

The operating point of one water cooled unit, Screw Chiller #9, was manipulated by the operator to be much lower than called for by the HVAC control system. The sound levels produced by this unit were significantly higher than sound levels produced by all other water-cooled screw chillers that were measured. The resulting atypical spectrum is not considered in the development of the baseline spectrum for water-cooled chillers.

A general trend in the remaining measurements is observed as follows: increasing approximately 3 dB per octave up to the 1 kHz one-third-octave-band, and decreasing approximately 4 dB per octave above this point, with a peak at the one-third octave band containing the LPF. The smoothed mean spectrum for water-cooled chillers is shown in Table 4-5.

Table 4-5: Smoothed Mean PWL Spectrum (dB ref. 1 pW) for the Water-Cooled Screw Chiller Measurements

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	79.4	78.1	76.8	77.4	79.7	80.2	80.3	81.2	82.7	84.9
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	65.8	68.9	68.2	69.2	72.4	73.6	73.7	70.0	69.5	69.4
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	83.9	81.8	79.6	78.5	77.8	75.9	73.8	70.6	66.9	63.1

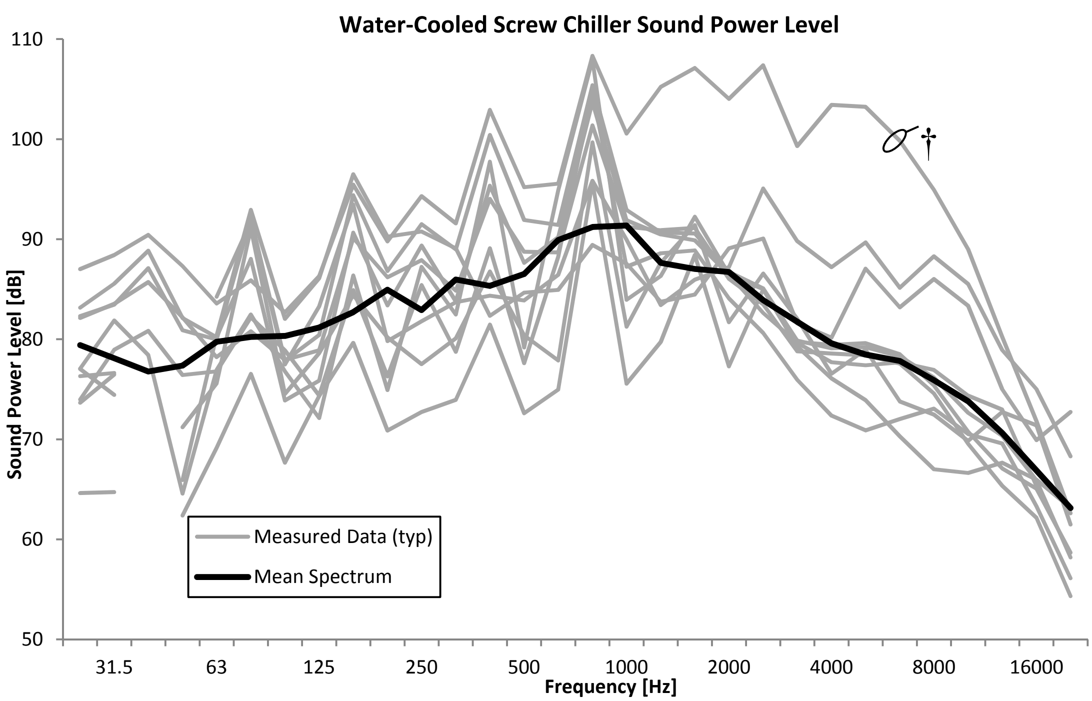

Figure 4-10: Comparisson of water-cooled chiller one-third-octave-band PWL spectra, along with a calculated mean spectrum. The spectrum indicated with a dagger (†) is for the unit that the operator was able to manually force into a lower operating point; this measurement was not considered in the development of the mean spectrum.

The measurements were analyzed on the basis of the total cooling capacity of the units, which ranged between 106 and 248 tons. However, it should be noted that three of the water-cooled chillers – Screw Chillers #9, #10, and #11 – were all identical models, with a 170 ton capacity, and these were all measured within a very narrow range of operation. The measured spectra are shown, grouped as follows: Screw Chiller #1, the 106 ton unit, in Figure 4-11; Screw Chiller #9, one of the three identical 170 ton units, in Figure 4-12; Screw Chiller #10 and Screw Chiller #11, the other two 170 ton units, in Figure 4-13; and Screw Chiller #8, the 248 ton unit, in Figure 4-14. The spectrum for Screw Chiller #9B is shown for reference only; this spectrum is marked with a dagger, and was not used in the development of the empirical correlation. The mean spectrum for water-cooled screw chillers is shown for reference in each chart.

The magnitudes of the spectra for the water-cooled screw chillers show a positive correlation with the total cooling capacity. There was found to be a somewhat better correlation for water-cooled units than for air-cooled units, in the sense that there are no cases of higher-capacity water cooled screw chillers producing less noise than their lower-capacity counterparts.

Looking at the frequency range between the 100 Hz and 5,000 Hz one-third-octave-bands, the average deviation from the mean spectrum for 106 ton, 170 ton, and 248 ton units is -4.7 dB, 0.9 dB, and 1.8 dB, respectively. As for air cooled units, this correlation is not linear with respect to the total capacity of the units, but is consistently a positive correlation. Also as with the air-cooled units, in this comparison a negative deviation indicates that the mean spectrum is generally above the measured spectra, and a positive deviation indicates that the measured spectra are generally above the mean spectrum.

The measurements were also analyzed on the basis of the operating point, expressed as a percentage of the total chilling capacity. Variation of the operating point was found to have an effect on the overall level of the spectra in most cases, although this effect was less correlated than it was found to be for air-cooled units. As with air-cooled units, a slight correlation was seen between the operating point and the magnitude of the narrow-band component.

Refer to Figure 4-11, showing the spectra measured for the 106 ton unit operating at 25% and 65% of its total capacity. The unit is shown to produce higher sound levels across the spectrum, when at the higher operating point – by an average of 4.7 dB over the 100 Hz to 5,000 Hz frequency range.

The spectra for Screw Chiller #9, one of the 170 ton units, operating at 72% during both visits, and also as it was forced to operate at 43% of its total capacity, are shown in Figure 4-12. Both measurements made while the unit was operating at 72% correlate very well, with an average variation of approximately ±1.3 dB over the 100 Hz to 5,000 Hz frequency range.

The spectra for the other two 170 ton units, operating at 61% (Screw Chiller #10A), and 68% (Screw Chiller #10B) of its total capacity, and Screw Chiller #11 operating at 69% of its total capacity are shown in Figure 4-13. The spectra for all of the units correlate quite well above the spectral peak in the 800 Hz one-third-octave-band – the measurement for the unit operating at 68% is , below the 800 Hz one-third-octave-band, screw chiller #11 is an average of 6.8 dB above the other two units, and above the 800 Hz one-third-octave-band, screw chiller #10B is an average of 3.3 dB below the other two units. At the 800 Hz one-third-octave-band, the magnitudes of all of the were within 1.7 dB of each other.

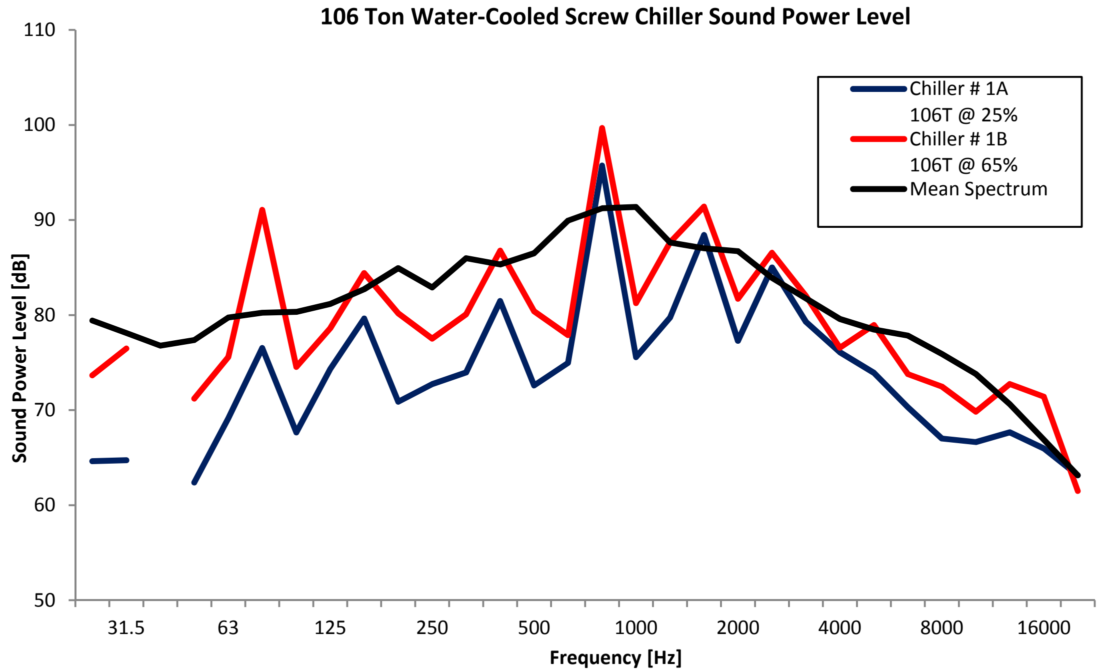

Figure 4-11: Comparisson of water-cooled chiller one-third-octave-band PWL spectra, for units with total cooling capacities of 106 HVAC tons

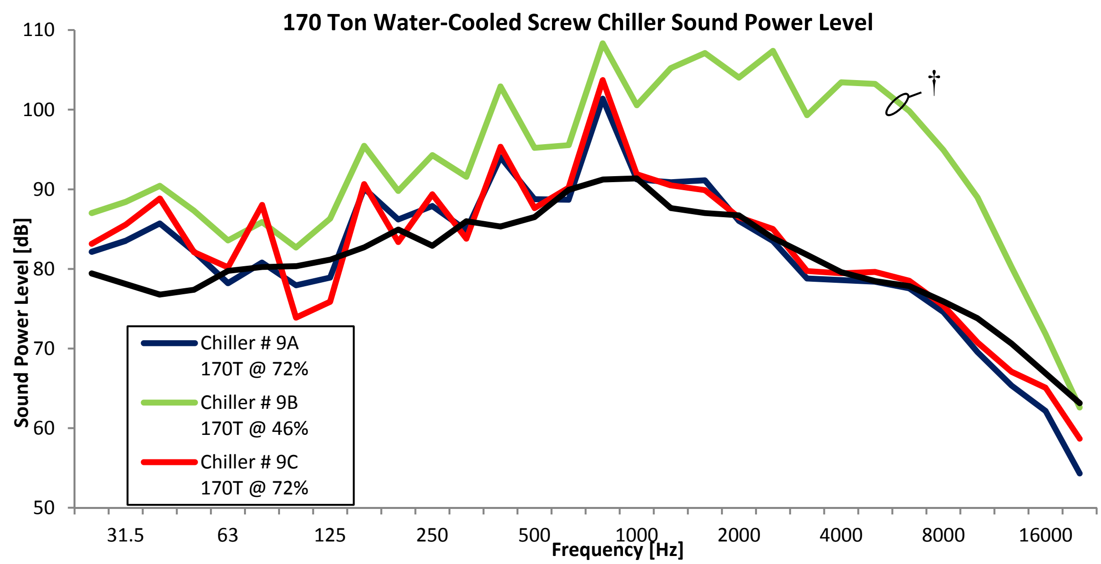

Figure 4-12: Comparisson of water-cooled chiller one-third-octave-band PWL spectra, for units with total cooling capacities of 170 HVAC tons. Screw Chiller #9B, indicated with a dagger (†)

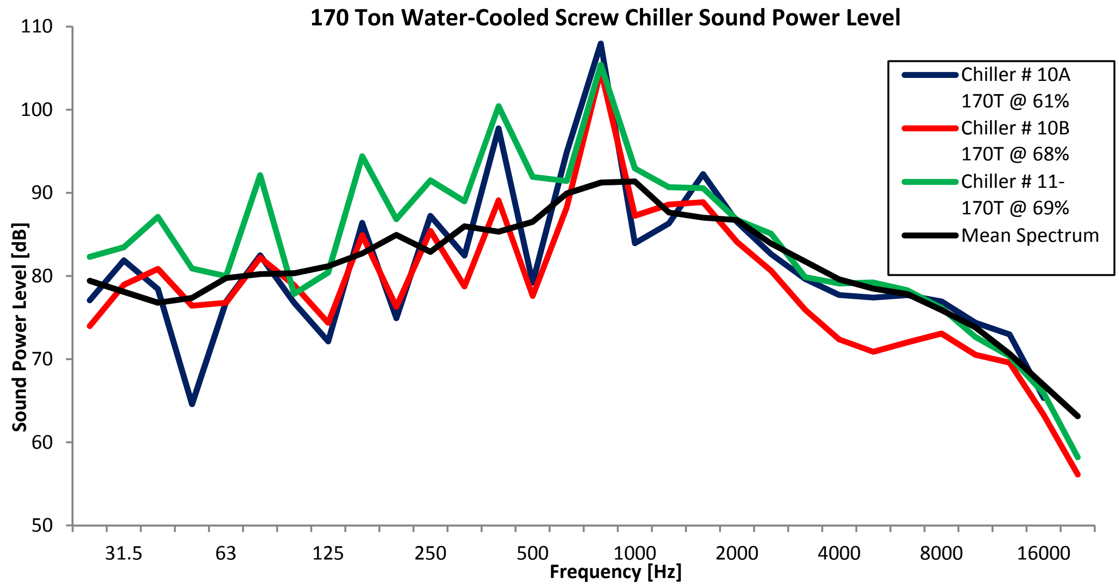

Figure 4-13: Comparisson of water-cooled chiller one-third-octave-band PWL spectra, for units with total cooling capacities of 170 HVAC tons

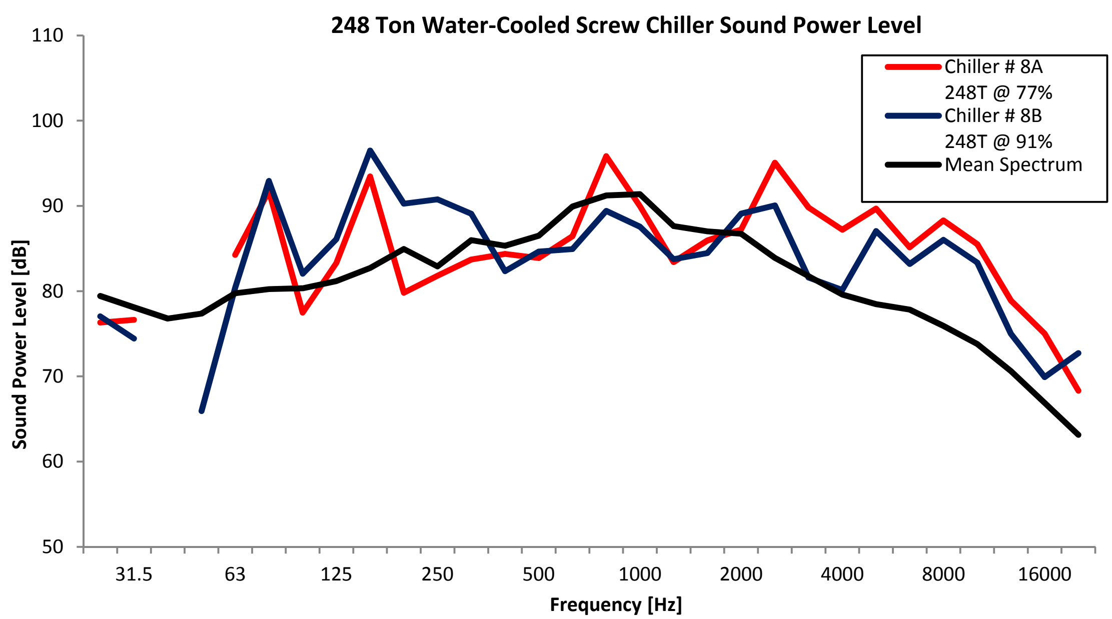

Figure 4-14: Comparisson of water-cooled chiller one-third-octave-band PWL spectra, for units with total cooling capacities of 248 HVAC tons

The spectra for the 248 ton unit operating at 77% and 91% of its total capacity is shown in Figure 4-14. Above the spectral peak in the 800 Hz one-third-octave-band, the spectra for this unit were generally higher at a lower operating point, and below this frequency this unit were generally higher at a higher operating point. At the 800 Hz one-third-octave-band, Screw Chiller #8A, at the lower operating point, was measured to be 6.4 dB above the same unit at the higher operating point.

In general, it is shown that, similar to the air-cooled screw chillers, the overall sound levels produced by water-cooled units increases with total cooling capacity, and with the operating point, and in many cases the magnitude of the narrow band component can increase when at a lower operating point.

4.2B: Water-Cooled Chiller Empirical Correlation

The form of the empirical correlation for water-cooled screw chillers is identical to the form presented in Equation 4.3 for air-cooled units. The terms c, p, m and K_{NB} were developed similarly to the air-cooled units.

The range of the overall PWL on the capacity of the water-cooled chillers, based on A-weighted and C-weighted averages, and compared to both cooling capacity and operating point are shown in Figure 4-15. Again, linear lines-of-best-fit are shown.

The terms m, c, and p, were found to be 10.101, 0.090 and 1.117, respectively. Again, a regression analysis was undertaken; the average R-squared value was found to be 0.486, and the minimum and maximum R-squared values were found to be 0.291, and 0.790, respectively. The adjusted spectrum, B, is shown in Table 4-6. The value of c was found to be 0.089, and the value of p was found to be 0.117; all three variables were calculated in a similar manner to the same variables for air-cooled screw chillers.

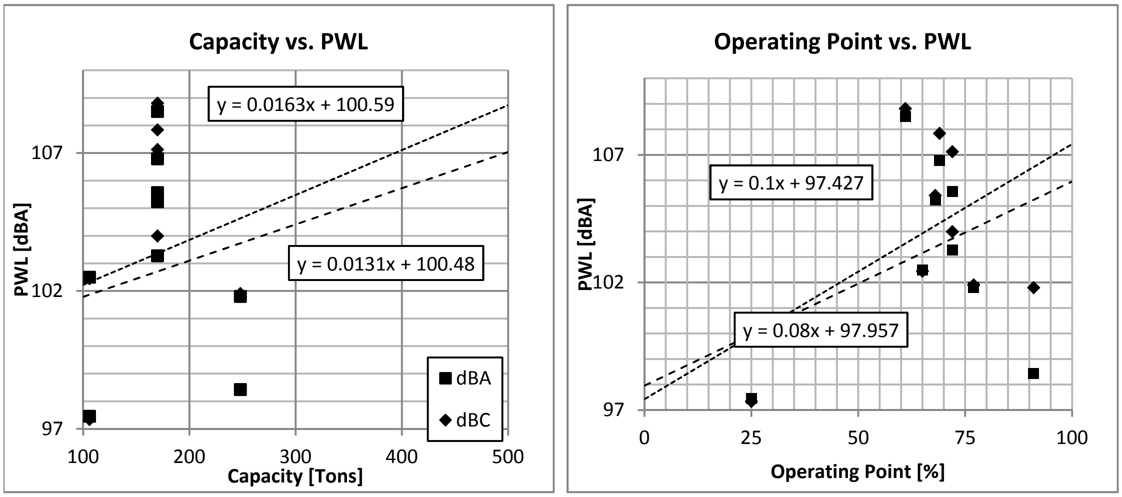

Figure 4-15: Comparisson of A-weighted PWL measurements vs. capacity and operating point.

The narrow-band term, K_{NB}, was developed in a similar manner to the air-cooled units, and the empirical correlation for PWL produced by water-cooled screw chillers, developed in the form presented in Equation (4.3), then can be written as:

$$L_W = B + 0.089\log(C) + 0.1173P + K_{NB} \qquad (4.5a),$$

$$K_{NB} = [0.85(19 - 0.2|C - 175|) + 0.15(14.5 - 0.3|P - 50|)] \qquad (4.5b)$$

The variables C and P are as defined for Equation (4.3), and similar to the previous equation. It is interesting to note that, in the case of water-cooled screw chillers measured – but not the air-cooled units, the one-third-octave-band containing the second harmonic of the LPF had a more pronounced peak than that of the LPF itself. This is accounted for in the model by applying the K_{NB} term to the one-third-octave-band containing the second harmonic of the LPF.

Table 4-6: Baseline PWL Spectrum (ref. 1 pW) for the Water-Cooled Screw Chiller Empirical Formula

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	69.1	67.8	66.5	67.1	69.5	70.0	70.0	70.9	72.4	74.7
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	72.6	75.7	75.0	76.2	79.6	80.9	81.1	77.3	76.7	76.4
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	73.6	71.5	69.3	68.2	67.5	65.6	63.5	60.3	56.6	52.9

4.2C: Water-Cooled Chiller Octave-Band Level Comparison

The measured octave-band spectra of the water-cooled units, shown in Figure 4-16, do not match the published curve nearly as well as the spectra for the air-cooled units. The measurements all show a spectral peak approximately two octaves above the peak in the published curve, and the overall level of the published curve is near the bottom of the range of the measured spectra.

Again, a regression analysis was undertaken for the octave-band-level measurements, and the average R-squared value was found to be 0.390, and the minimum and maximum values were found to be 0.090 and 0.636, respectively.

The general disagreement between the published spectrum and the measurements from water-cooled screw chillers confirms the inference mentioned in Section 4.1C, that the limited data set from which the published spectrum was formulated comprised of air cooled units without extraordinary noise control measures taken.

An octave-band spectrum is proposed for water-cooled screw chillers, and is shown in Figure 4-16 and Table 4-7.

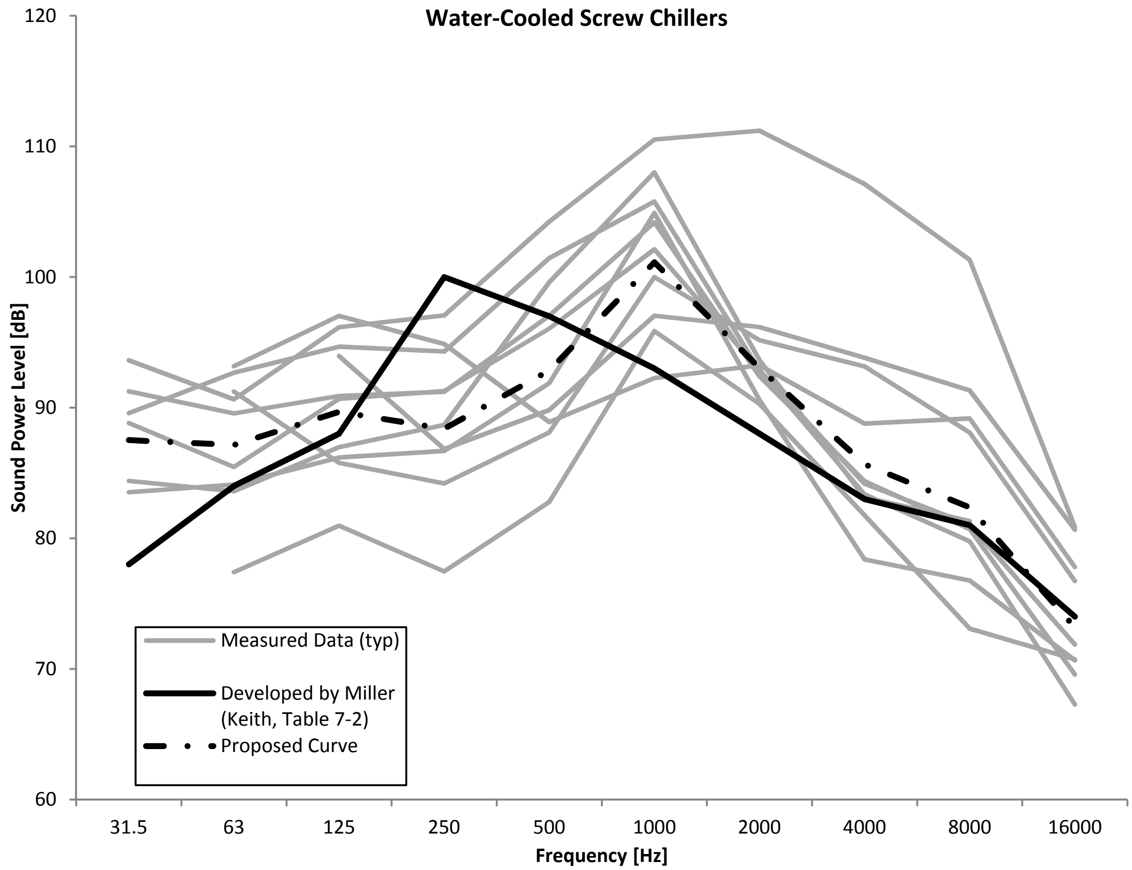

Figure 4-16: Comparisson of water-cooled screw chiller PWL measurements with Miller's published spectrum and proposed octave-band spectrum

Table 4-7: Typical Octave-Band Spectrum for Water-Cooled Screw Chiller PWL (ref. 1 pW)

Frequency [Hz]	**31**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
PWL ref. 1pW [dB]	88	90	92	91	96	103	93	89	86

Broadband Metric	**dB**	**dBA**
PWL ref. 1pW [dB]	105	101

4.2D: Water-Cooled Chiller SQI Comparison

The range of SQI ratings for the water-cooled screw chillers is shown in Figure 4-17. These ratings range between 25.1 and 31.6, with an average of 27.6. Note that the 31.6 SQI rating is from Chiller #9B, which was not used in the development of the empirical formula; the highest SQI rating for water-cooled units that were considered in the development of the empirical formula was 28.2, and the standard deviation for this reduced data set was 0.86. The SQI ratings for water-cooled chillers are tabulated in Table 4-8; in this table, the chillers are arranged in order of increasing overall cooling capacity and operating point for a given cooling capacity.

Similar to the air-cooled units the SQI ratings are generally higher for units with higher cooling capacities, with the exceptions of Screw Chillers #10A and #11, and a given chiller at a higher operating point generally has a higher SQI rating than at a lower operating point, again witht the exception of Screw Chiller 310A.

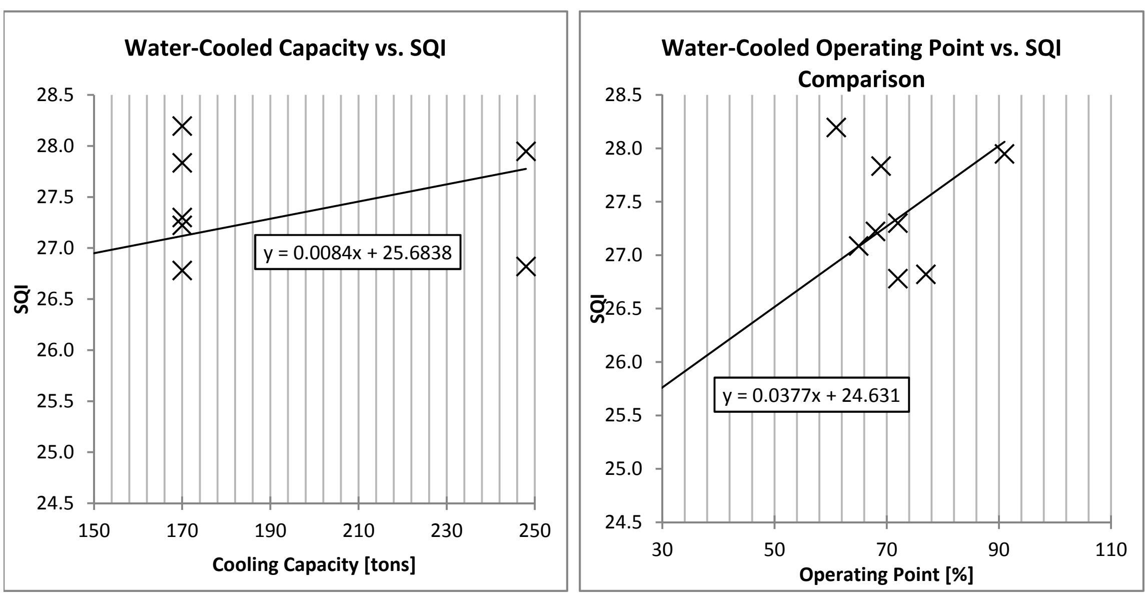

Figure 4-17: Comparisson of water-cooled screw chiller PWL measurements with Miller's published spectrum

Table 4-8: Summary of water-cooled screw chiller SQI ratings

ID	Cap. [tons]	Operating Pt. [%]	SQI
1A	106	25	25.1
1B	106	65	27.1
9B	170	46	31.6
10A	170	61	28.2
10B	170	68	27.2
11	170	69	27.8
9A	170	72	26.8
9C	170	72	27.3
8B	248	77	26.8
8A	248	91	27.9

Chapter 5: Conclusion[4]

5.1: Project Summary

Noise problems associated with screw chillers are well documented, and a common thread in many of the documented complaints is a prominent narrow-band component, [15; 21] the frequency of which is typically associated with the rotational velocity of the driven (usually male) rotor [6].

Screw chillers stand out as one of the few commonly used types of HVAC equipment for which there is not an empirical correlation for typical PWL spectrum. Correlations have been developed for HVAC chillers with scroll and reciprocating compressors, as well as different types of fans, pumps, cooling towers, and several other categories of mechanical and industrial equipment. These correlations typically produce PWL spectra on an octave-band basis, with variables such as airflow rates, rotational velocities, and pressure differentials – parameters a mechanical engineer would be able to reasonably estimate relatively early in a design, and then share with a noise control engineer. Many of the empirical correlations that are in use today are attributed to the work of Laymon Miller from the 1950s through his retirement in 1981. It should be noted that Miller did publish a typical octave-band PWL spectra for screw chillers in the notes for the noise control course that he founded; however, no correlations relating the spectra to operating conditions are provided [4].

The goal of this project was to begin development of empirical correlations for the PWL produced by air- and water-cooled screw chillers, as functions of the overall

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[4] The work in this chapter was part of the basis for a paper presented at Noise-Con 2017, which Daniel Alon Hemme was the primary author of, with co-authors David A. Nelson, and Preston S. Wilson.

Characterization of Sound Power Level Spectra Produced by HVAC Chillers with Double Helical Rotary Screw Compressors Under Various Operating Conditions. **Hemme, Daniel A, et al.** Grand Rapids, MI: Noise-Con 2017.

cooling capacity of the chiller, the operating point of the unit, expressed as a percentage of the overall capacity, and the rotational velocity of the driven rotor. In order to more accurately describe the prominent narrow-band component, these correlations were developed on a one-third-octave-band basis, from which octave-band and broadband levels, and other metrics can be calculated.

To accomplish this goal, PWL was determined for several screw chillers in service in the Austin, Texas area, based on measurements using the two-surface method, as defined in ASTM E1124-10 [25]. Measurements were taken for as many units as possible under multiple operating conditions.

The two-surface method requires that SPL measurements be taken over as much of the exposed surface area of the unit under test as possible, at two known distances from the source. The pair of measurements are taken, using sweeping microphone paths, over inner and outer measurement surfaces, forming concentric parallelepipeds, as depicted in Figure 1-6 and Figure 2-8.

With the SPL measured over the pair of surfaces, PWL can be written entirely in terms of the inner and outer measurement surface areas, and the RMS SPL measurements over the same surfaces, as discussed in Chapter 1 – refer to Equation (1-15) [25].

The experimental equipment setup consisted of hardware and software that was configured to record audio at the screw chiller installation site according to the two-surface method, and process the recorded audio to generate PWL data at one-third-octave-band frequency resolution.

The requirements of the measurement apparatus are defined in ASTM E1124-10 [25]. These requirements include a matched and calibrated pair of microphones, an audio recording device and frequency spectrum analyzer with minimum 0.1 dB resolution, and a microphone mounting apparatus. A diagram of the two-surface measurement setup is shown diagrammatically in Figure 2-2. A complete description of the hardware and software used for this research, as well as the testing and calibration that was undertaken for the measurement setup prior to obtaining screw chiller measurements, is available in Chapter 2; a more in-depth look at the data analysis software custom developed for this project is available in Appendix B. A set of site visit procedures was developed, and a Site Data Sheet was created, in order to ensure that all of the necessary data points were recorded, and that the site visits were conducted as efficiently and uniformly as possible.

A total of eleven screw chillers were visited – six air-cooled units and five water-cooled units. As much as possible, each chiller was measured in the spring and again in the summer, in order to experience different loading conditions, for a total of twenty measurements. Each of the screw chillers measured and the measurement sites are described in Chapter 3, and the site data sheets for all measurement sites are shown in Appendix A.

The measured data is discussed and analyzed in Chapter 4. Analysis was carried out on a one-third-octave-band basis, an octave-band basis, and by comparing the SQI ratings associated with the measured spectra.

The one-third octave band analysis consisted of a study into the effects of overall chiller capacity, as well as operating point expressed as a percentage of the overall capacity, on the PWL spectrum produced by the unit. Empirical correlations on a one-third-octave-band basis were developed for both air-cooled and water-cooled screw chillers.

Measured octave-band level spectra for air- and water-cooled screw chillers were compared against a typical spectrum published by Miller [4]. The spectra measured for air-cooled units were found to agree relatively well with the published spectrum, leading to the inference that the published spectrum was developed based off of measurements of air-cooled units. The spectra measured for water-cooled units did not agree with Miller's spectrum, and an octave-band spectrum for these units is presented in this thesis.

The SQI ratings of the screw chillers were also analyzed and compared against other SQI ratings for the same type of chiller. In general, the SQI ratings for each type of screw chiller were found to vary over a relatively narrow range, and were found to generally increase with increasing capacity and operating point.

There were some compromises and limitations inherent to this study that may have implicatios on the accuracy and precision of the results. In most cases a side, or a portion of a side, of the unit being investigated was inaccessible due to piping or other obstructions. Furthermore, in all cases the top of the unit was inaccessible due to the height of the units, and the property owners' collective reluctance to allow scaffolding to be erected. The inaccessible sides were accounted for by using calculating PWL according to the provisions defined in ASTM E1124-10 [25], or by using measurements from the side of the chiller opposite of the inaccessible side. The inability to take measurements at the top surface was accounted for by conservatively applying SPL measured at a side surface to the area of the top surface. The inaccessibility of the top of all of the screw chillers is assumed to be a significant omission, as the tops of the units, often include other noise sources, such as axial fans in air-cooled units, which are likely not fully described in the measurements taken at the side surfaces.

The equipment available included only Type II microphones, with ¼" elements, and "prosumer" audio equipment. Additionally, the conditions in which the measurements were made, with the microphones in the nearfield of the equipment being investigated, and often outdoors, make the measurements susceptible to low-frequency anomalies such as standing waves and wind noise. This may be exacerbated by the inability to calibrate the measurement system below approximately 125 Hz, due to the low-frequency limitation inherent to the anechoic chamber at UT Austin. These limitations are likely the cause of the wildly varying low-frequency readings, and for the frequency bands for which no valid calculation could be made by the two-surface method.

5.2: Future Work

There is much room for future work in the pursuit of empirical correlations for one-third-octave-band spectra for air- and water-cooled screw chillers. The correlations developed for this thesis are based on a very limited set of chillers, being used in a relatively narrow band of the availale range of operation. The equipment available for measurement and analysis was largely "prosumer" grade hardware, and software developed by the author. Additional field measurements for both types of chillers, over a wider range of operating conditions, as well as higher-grade hardware, and commercially developed software, would be expected to result in increased precision and accuracy.

Additionally, the measurements made at the site visits are of as much of the side surface areas as was accessible, but in no instance was the top of the unit accessible for measurement; this issue, and others involving the testing and calibration of the measurement setup are discussed in further detail in Chapter 2.

Furthermore, manufacturer-provided sound data for the various screw chillers that were measured was found to be unavailable. The author contacted manufacturer representatives, inquiring about such data, but invariably received either no response at all, or a response indicating that they would not, or could not, provide the requested data. It would be helpful to correlate the measured data with manufacturer-provided data, in order to both verify the manufacturer-provided data, and also to attempt to quantify the effect of other pieces of equipment, such as pumps, that were in operation in close proximity to many of the screw chillers. It should be noted that there are already existing empirical correlations for pumps of various designs, and at various operating conditions [4], which could then be used in conjunction with the correlations for screw chillers, to get a more accurate idea of the resulting sound levels around the equipment.

The spreadsheet used to keep track of the measured data, and analyze the results, is setup to accept additional one-third-octave-band PWL measurements, and refine the analysis accordingly. If additional screw chillers are available for measurement, it would be relatively easy to expand the data set used for this analysis, and thereby increase the accuracy and precision of the empirical correlations that were developed.

Appendix A: Site Visit Information & Raw Data

The Site Data Sheets for each of the measurements are presented in this Appendix, along with the tabulated one-third-octave-band PWL spectrum, the broadband PWL, unweighted, A-weighted, and C-weighted, the SQI rating and the R-squared coefficient of the modeled spectrum with respect to the calculated spectrum. The measured and calculated spectra are also shown graphically. Octave-band level PWL spectra for each of the screw chillers is presented in Table A-21.

1A

Location: PfISD - Palmer Ln E.S.	Test Date: 10 MAR 2016
	Contact: Alex Negrito 512-201-7437; Chris Townsend
Address: 1806 Palmer Ln 78727; Park in Lot @ service drive W of bldg	

Manufacturer: Carrier	Model: 30HXC106RY	# Comps: 2(HH) 1	# Fans: —	Temp: 74 °F
Capacity: 106 Tons	Oper. Pt.: 25 %	3500 RPM	Inst. Date:	V_{wind}: — fpm
kW [0-60] Hz	LxDxH: 84" x 60" x 73.5" ~~ft~~	$SPL_{10'}$ dBA	f_c: 535 Hz	
Top: d_1 — in d_2 — in	Side: d_1 12.75 in	d_2 54.25 in		Cal. @ 94 / 114 dB

NOTES

Ivie #3

DIMENSIONED SKETCH

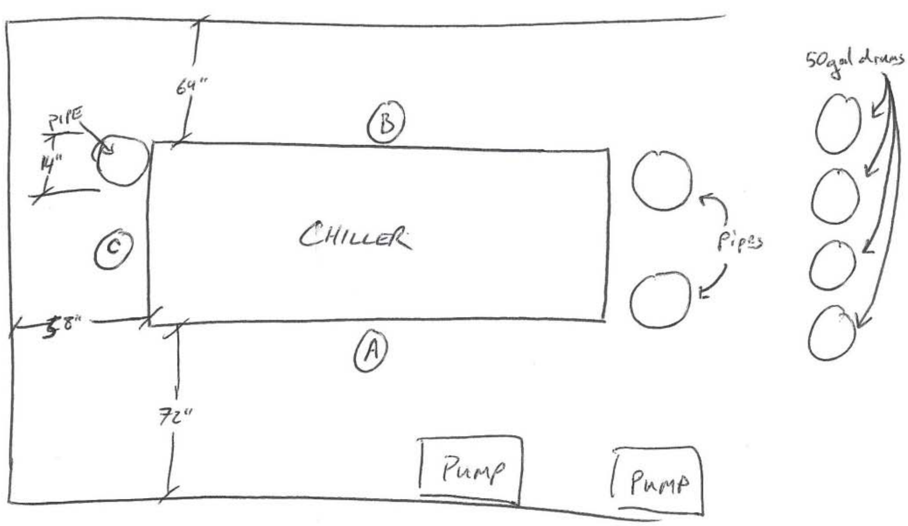


Figure A-1: Site Data Sheet for Screw Chiller #1A

Table A-1: Measurement Results for Screw Chiller #1A

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	64.6	64.7	--	62.4	69.1	76.5	67.7	74.3	79.6	70.9
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	72.7	74.0	81.5	72.6	75.0	95.7	75.6	79.7	88.4	77.3
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	85.0	79.3	76.1	73.9	70.3	67.0	66.6	67.7	66.0	63.1
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	97.4	97.5	97.3	25.1	0.291					

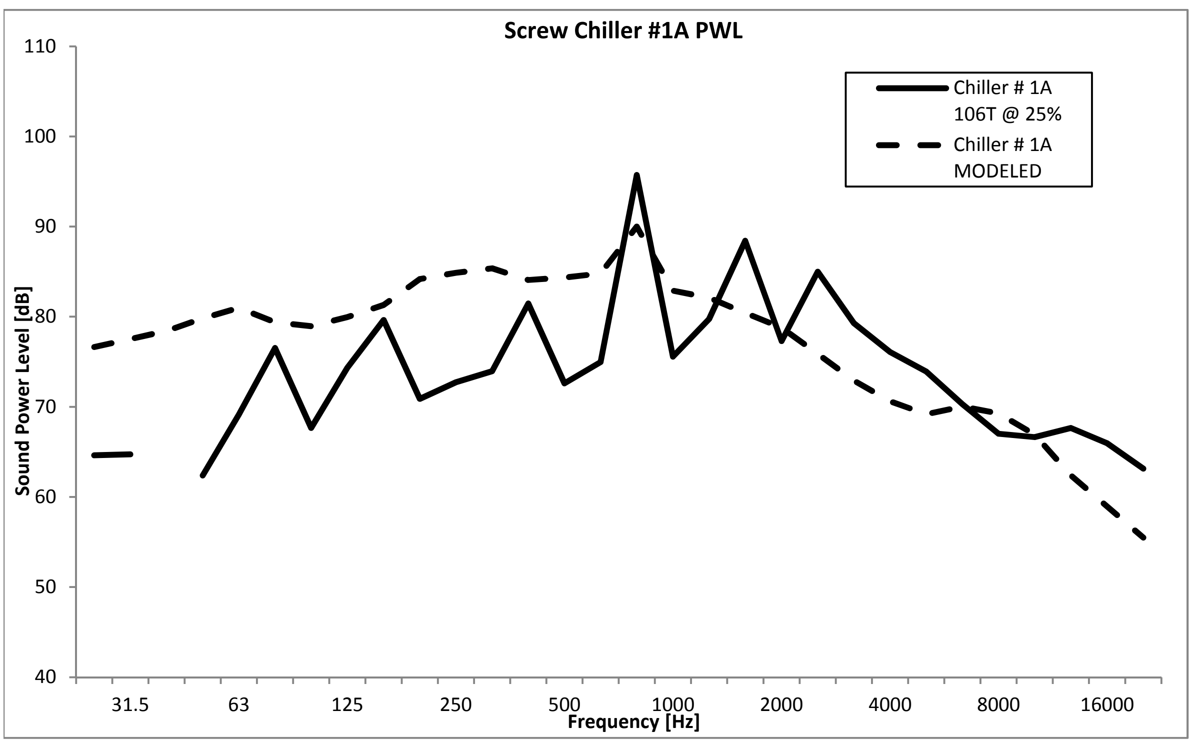


Figure A-2: Measurement Results for Screw Chiller #1A

1B

Location: Palmer Ln E.S.	Test Date: 23 Aug 2017
Address:	Contact: Alex Negrito

Manufacturer: Carrier	Model: 30HXC106RY	# Comps: 1 running	# Fans: ~~—~~	Temp: 94 °F
Capacity: 106 Tons	Oper. Pt.: 65 %	3500 RPM	Inst. Date:	V_{wind}: ~~—~~ fpm
kW [0-60] Hz	LxDxH: 84" x 60" x 74" ft	$SPL_{10'}$ dBA	f_c Hz	
Top: d_1 ~~—~~ in, d_2 ~~—~~ in	Side: d_1 14 in	d_2 35 in		Cal. @ 94 / 114 dB

NOTES

Ivie # 485

DIMENSIONED SKETCH

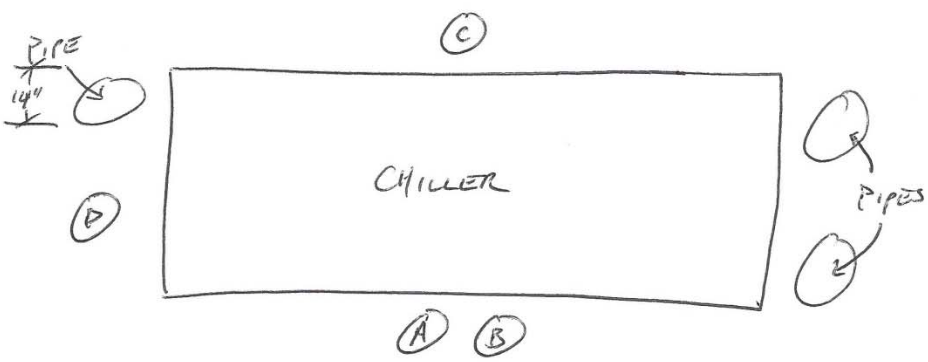


Figure A-3: Site Data Sheet for Screw Chiller #1B

Table A-2: Measurement Results for Screw Chiller #1B

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	73.7	76.5	--	71.2	75.6	91.1	74.5	78.6	84.4	80.2
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	77.5	80.1	86.8	80.4	77.9	99.7	81.3	87.6	91.4	81.7
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	86.6	82.0	76.6	79.0	73.8	72.5	69.8	72.7	71.4	61.5
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	102.7	102.5	102.4	26.3	0.313					

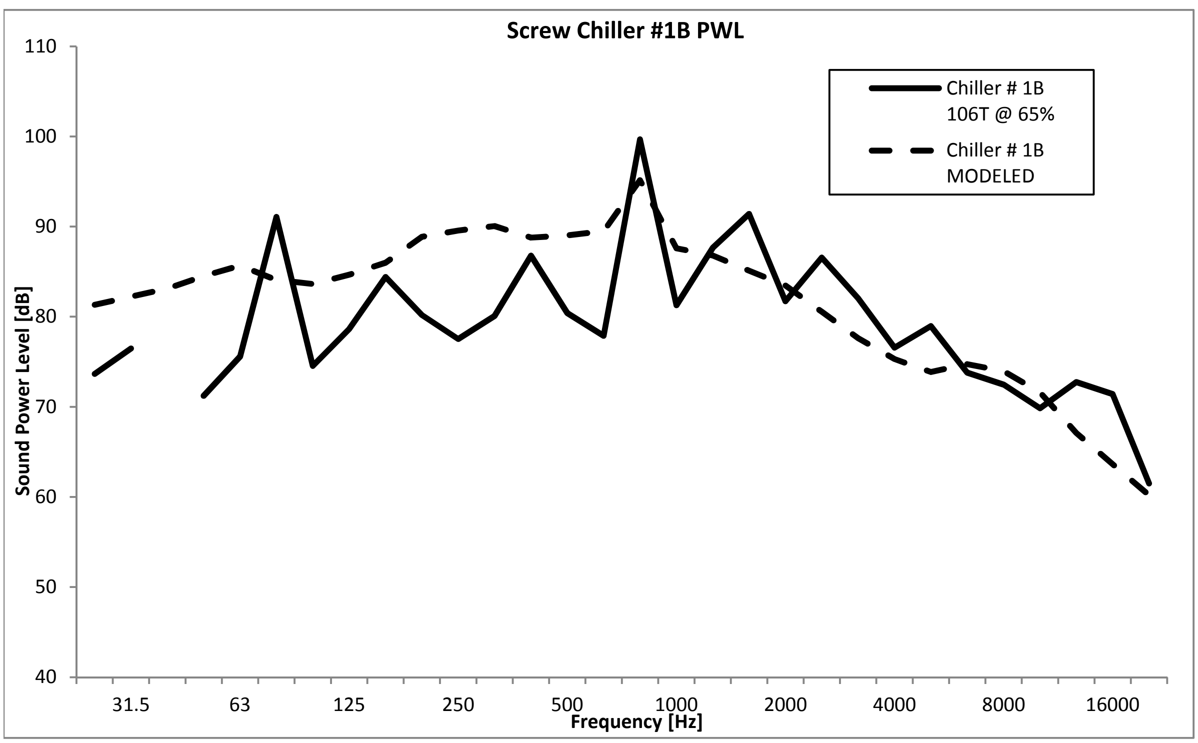


Figure A-4: Measurement Results for Screw Chiller #1B

2A

Location: 911 W 38th St		Test Date: 24 MAR 2016	
Address		Contact: GLEN HARCROW 512-215-1692 Steve	

Manufacturer: YORK	Model: YCIV0247SA46	# Comps: 2	# Fans: 10	Temp: 74 °F
Capacity: 247 Tons	Oper. Pt.: 35 %	RPM	Inst. Date: 2012	V_{wind}: 220 fpm
kW [0-60] Hz	LxDxH: 230" x 88" x 87" ft	$SPL_{10'}$ dBA		f_c: 549 Hz
Top: d_1 ~~in~~ ~~d_2~~ in	Side: d_1 14 in	d_2 45 in		Cal. @ 94 / 114 dB

NOTES

Ivie #3

DIMENSIONED SKETCH

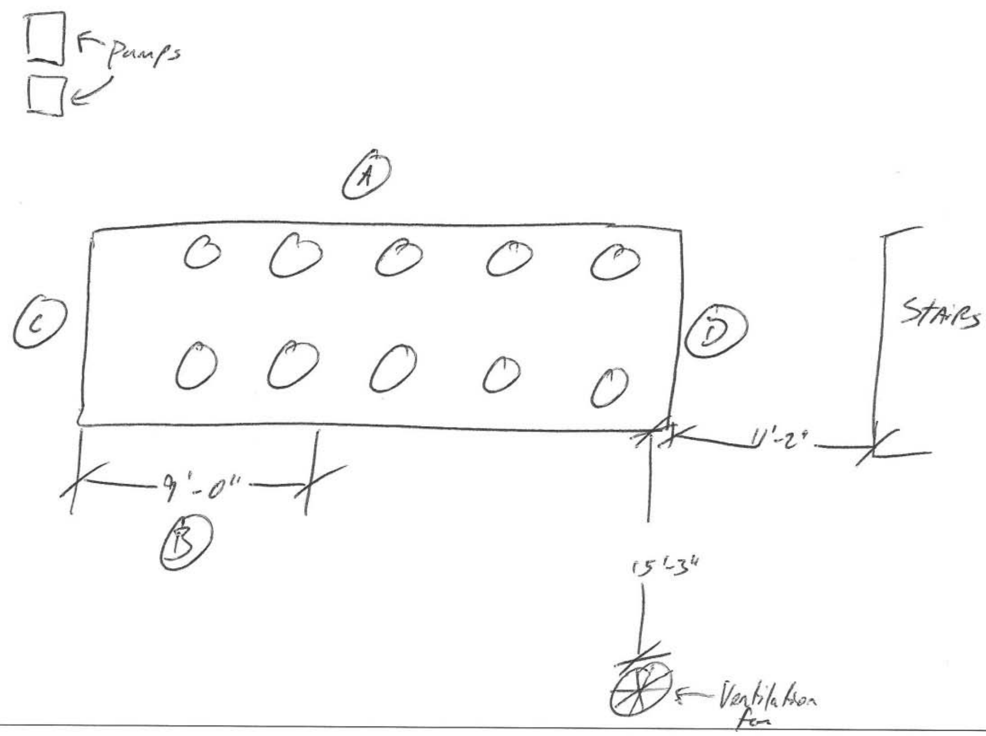


Figure A-5: Site Data Sheet for Screw Chiller #2A

Table A-3: Measurement Results for Screw Chiller #2A

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	82.3	--	--	--	88.7	100.2	81.7	87.9	94.8	90.5
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	90.2	93.5	90.8	85.9	97.2	89.1	93.5	90.3	85.3	83.9
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	83.8	77.5	69.0	72.7	72.4	79.2	70.2	61.9	63.6	63.0
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	103.0	99.7	103.0	26.1	0.832					

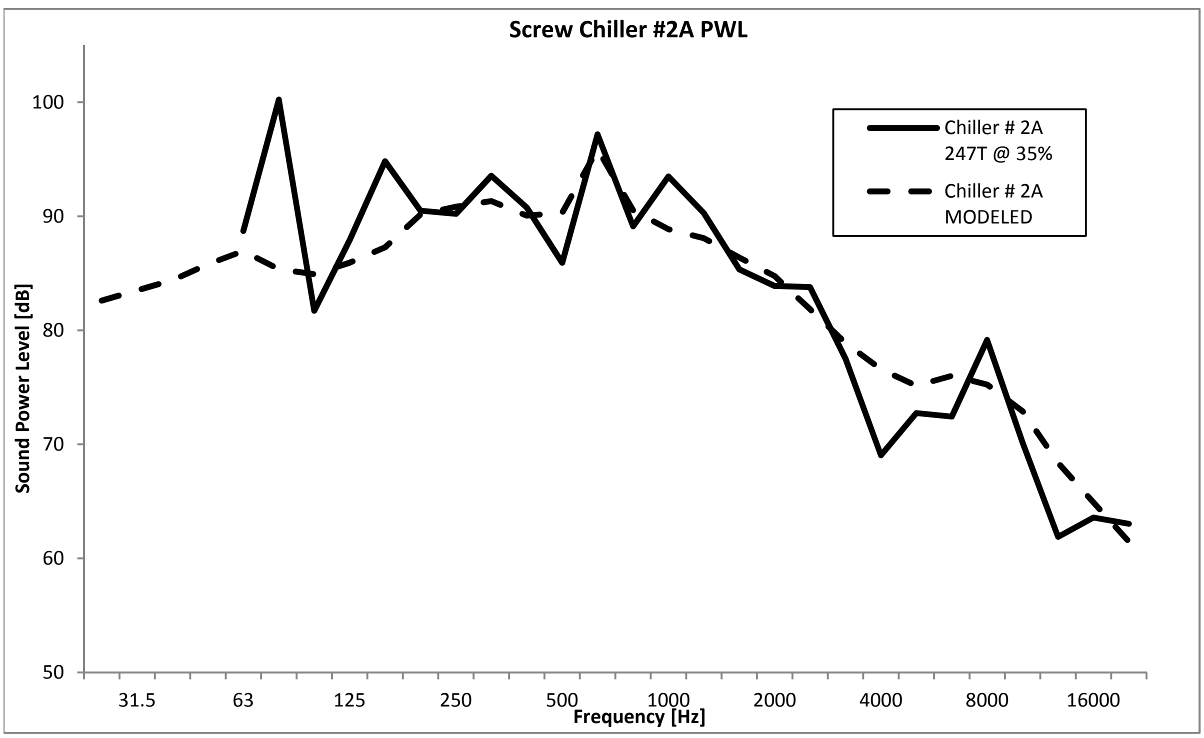


Figure A-6: Measurement Results for Screw Chiller #2A

2B

Location 911 W 38th St.	Test Date 9 SEPT 2016
Address	Contact Glen Harcrow Steve

Manufacturer YORK	Model RGF 24MAR	# Comps 2	# Fans 10	Temp 94 °F
Capacity 247 Tons	Oper. Pt. 53 %	RPM	Inst. Date	V_{wind} 100 fpm
kW [0-60] Hz	LxDxH 230"x88"x87" ft	$SPL_{10'}$ dBA	f_c Hz	
Top: d_1 ~~in d_2~~ in	Side: d_1 14 in	d_2 56 in		Cal. @ 94 / 114 dB

NOTES

Ivie #384

DIMENSIONED SKETCH

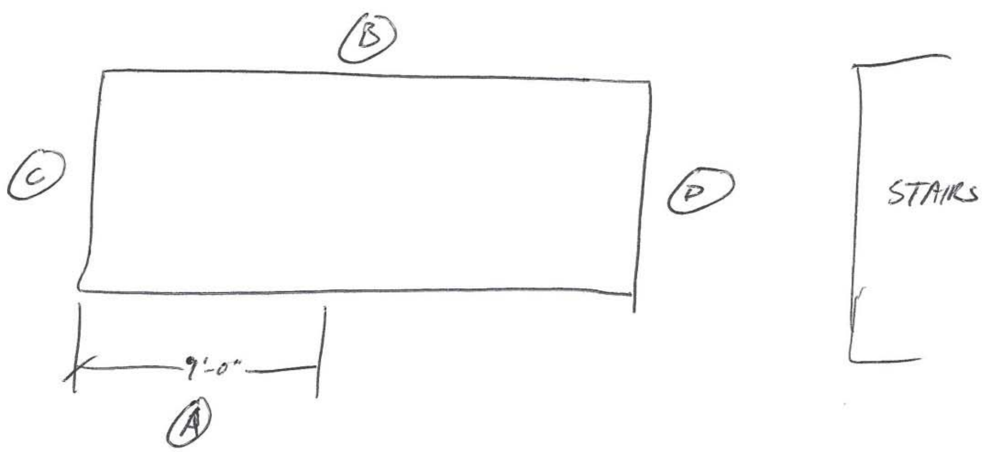


Figure A-7: Site Data Sheet for Screw Chiller #2B

Table A-4: Measurement Results for Screw Chiller #2B

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	--	82.4	--	82.8	92.6	102.3	86.4	89.8	97.1	93.4
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	90.5	94.5	92.4	84.1	98.7	89.5	94.7	91.8	87.8	85.5
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	84.4	80.7	73.5	73.5	68.6	77.1	68.3	63.7	65.0	63.5
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	106.8	101.1	106.5	26.5	0.550					

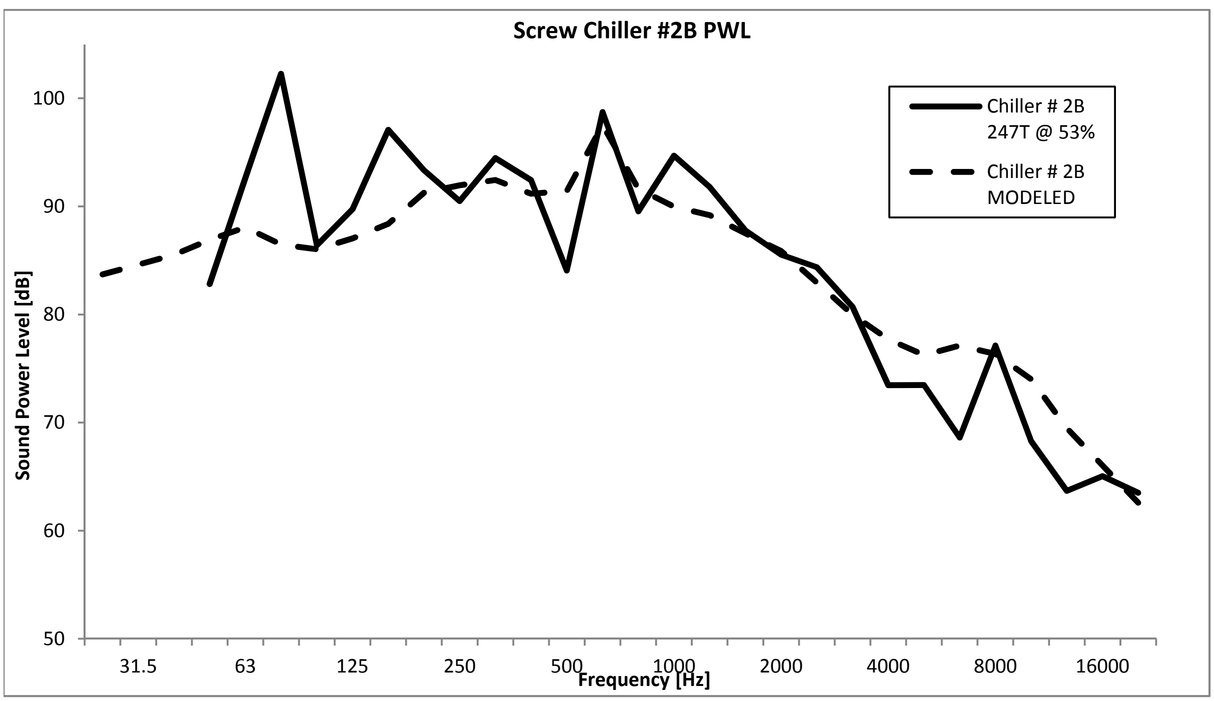


Figure A-8: Measurement Results for Screw Chiller #2B

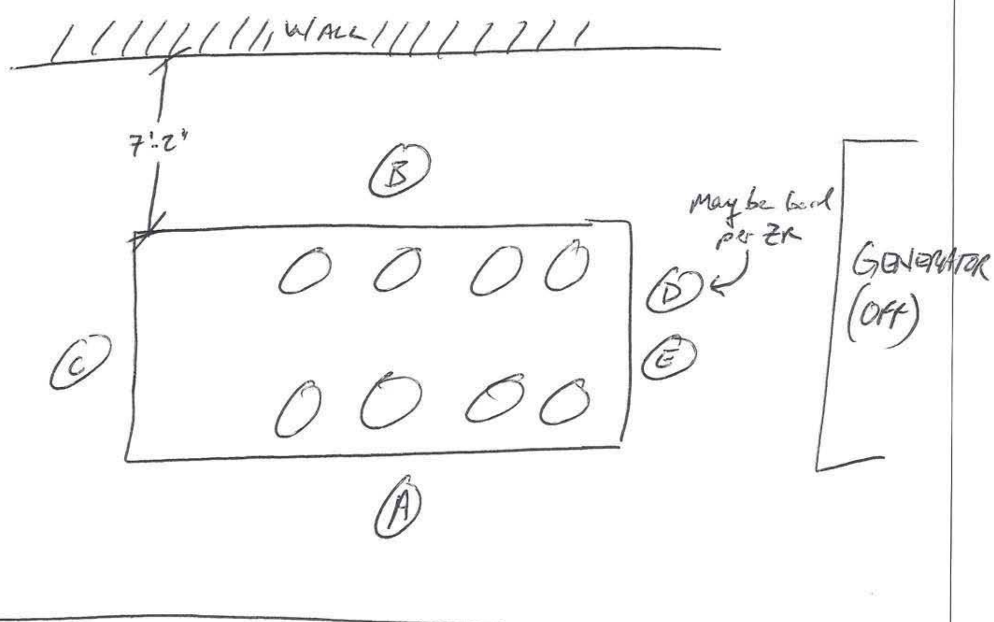
NOTE: LOCATION AND CONTACT INFORMATION OMMITTED AT REQUEST OF OWNER

3A

Location [redacted]			Test Date 6 April 2016		
Address [redacted]			Contact [redacted]		
Manufacturer York	Model YCAV0157VA46		# Comps 2	# Fans 8	Temp 81 °F
Capacity 157 Tons	Oper. Pt. 31 %	RPM	Inst. Date 2006		V_{wind} ~180 fpm
kW [0-60] Hz	LxDxH 230"x88"x87"		$SPL_{10'}$ dBA	f_c Hz	
Top: d_1 ~~in~~ ~~d_2~~ in	Side: d_1 11.75 in	d_2 38.5 in			Cal. @ 94 / 114 dB

NOTES

DIMENSIONED SKETCH



pumps in pit below

Figure A-9: Site Data Sheet for Screw Chiller #3A

Table A-5: Measurement Results for Screw Chiller #3A

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	--	76.6	75.0	98.4	85.7	70.9	89.1	81.4	92.5	88.7
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	89.7	90.4	88.5	89.2	86.6	91.2	86.5	87.3	87.0	86.4
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	82.1	74.8	69.6	74.0	73.6	78.1	72.5	70.4	69.1	62.3
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	102.7	97.3	102.3	25.2	0.772					

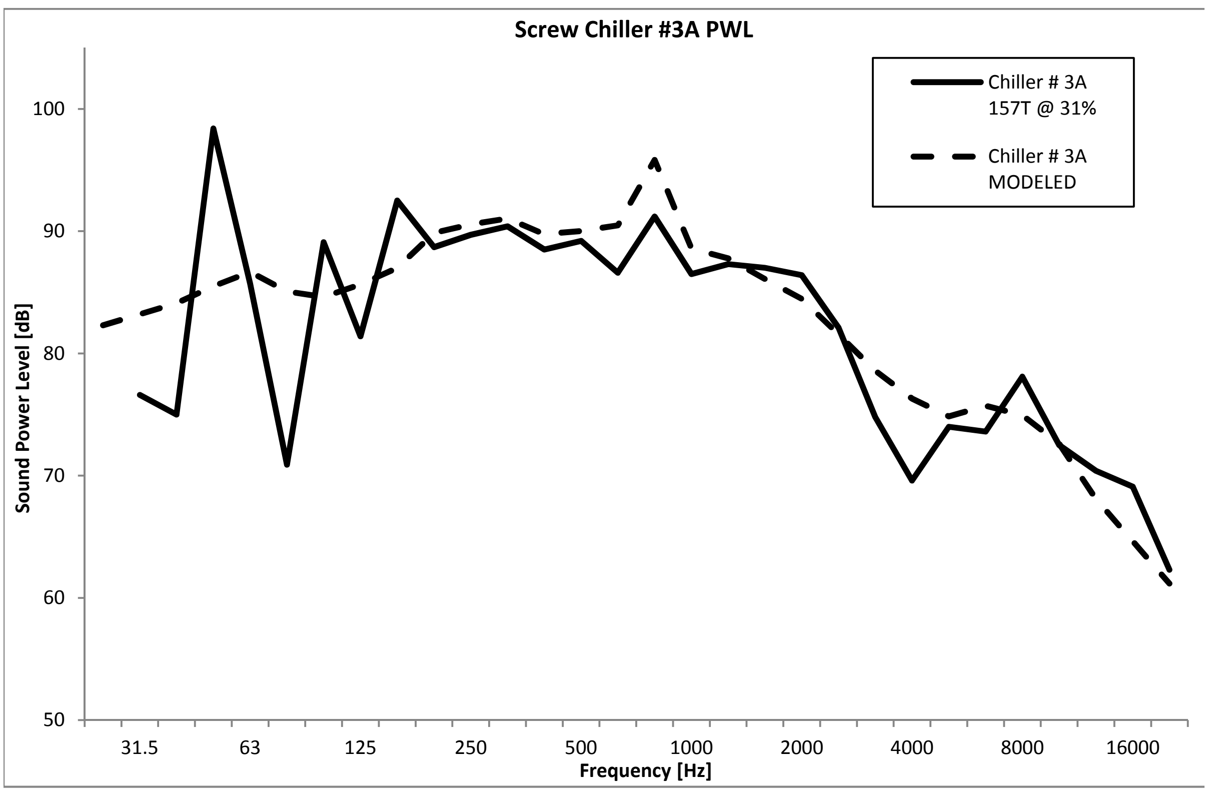


Figure A-10: Measurement Results for Screw Chiller #3A

NOTE: LOCATION AND CONTACT INFORMATION OMMITTED AT REQUEST OF OWNER (3B)

Location [redacted]			Test Date 21 Jul 2016		
Address [redacted]			Contact [redacted]		
Manufacturer York	Model YCAV0157 VA46		# Comps 2	# Fans 8	Temp 101 °F
Capacity 157 Tons	Oper. Pt. %	RPM	Inst. Date 2006		V_{wind} 135 fpm
kW [0-60] Hz	LxDxH 230"x88"x87" ft		$SPL_{10'}$ dBA		f_c 172 Hz
Top: d_1 ~~in d_2~~ in	Side: d_1 17.75 in	d_2 40.5 in			Cal. @ 94 / 114 dB

NOTES

IVIE# 7

DIMENSIONED SKETCH

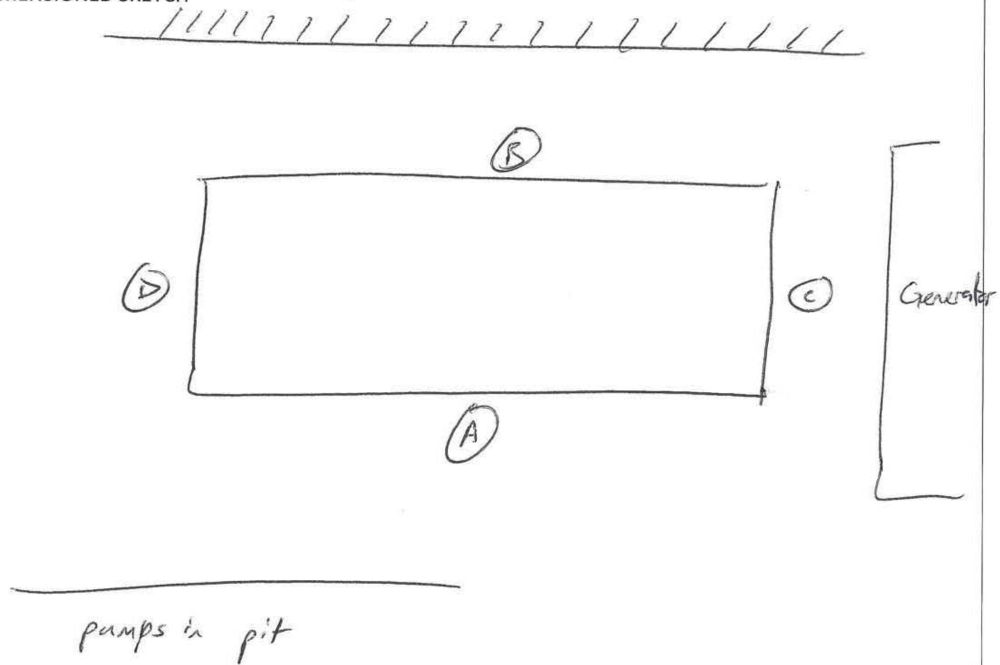


Figure A-11: Site Data Sheet for Screw Chiller #3**B**

Table A-6: Measurement Results for Screw Chiller #3B

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	83.4	83.5	84.9	88.2	95.5	84.2	95.4	90.0	95.1	95.1
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	101.3	91.6	90.8	93.8	90.1	94.9	91.4	84.3	91.1	86.1
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	84.5	86.2	84.3	80.1	83.6	82.1	80.9	76.9	70.9	65.4
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	104.9	101.2	104.7	26.0	0.781					

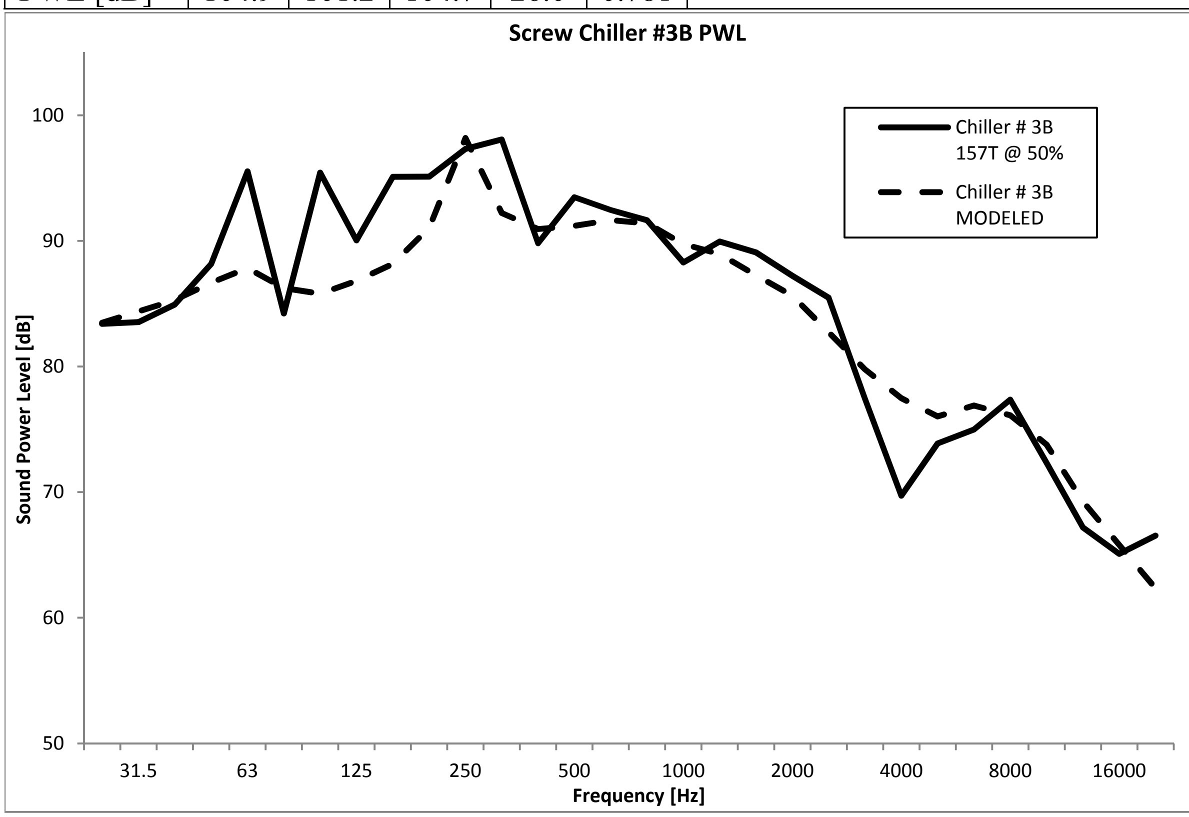


Figure A-12: Measurement Results for Screw Chiller #3B

4A

Location 901 W 38th #1			Test Date 14 APRIL 2016		
Address			Contact Glen Harcrow 512 215-1692		
Manufacturer Carrier	Model 30GXN153		# Comps 2	# Fans 10	Temp 81 °F
Capacity 153 Tons	Oper. Pt. 31 %	RPM	Inst. Date 2013		V_{wind} 140 fpm
kW [0-60] Hz	LxDxH 231"x 85"x 80" ft		$SPL_{10'}$ dBA	f_c	Hz
Top: d_1 ~~in~~	~~d_2~~ in	Side: d_1 11.75 in	d_2 38.75 in		Cal. @ 94 / 114 dB

NOTES

DIMENSIONED SKETCH

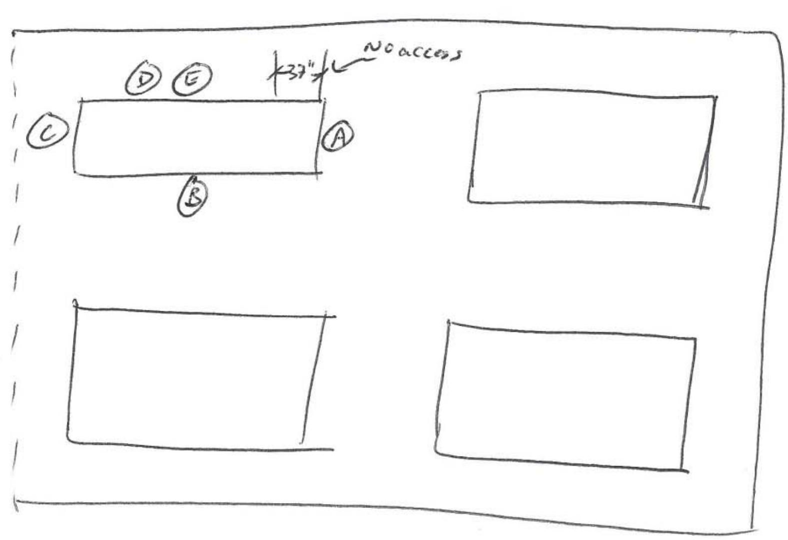


Figure A-13: Site Data Sheet for Screw Chiller #4A

Table A-7: Measurement Results for Site Visit #4A

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	96.8	89.0	79.6	85.3	81.6	85.6	81.7	84.9	82.8	81.5
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	99.4	87.1	90.6	94.2	91.8	90.6	86.6	87.0	88.4	82.8
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	79.9	80.1	80.4	77.4	77.0	79.0	75.2	69.6	57.4	62.0
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	102.9	98.8	102.9	25.7	0.682					

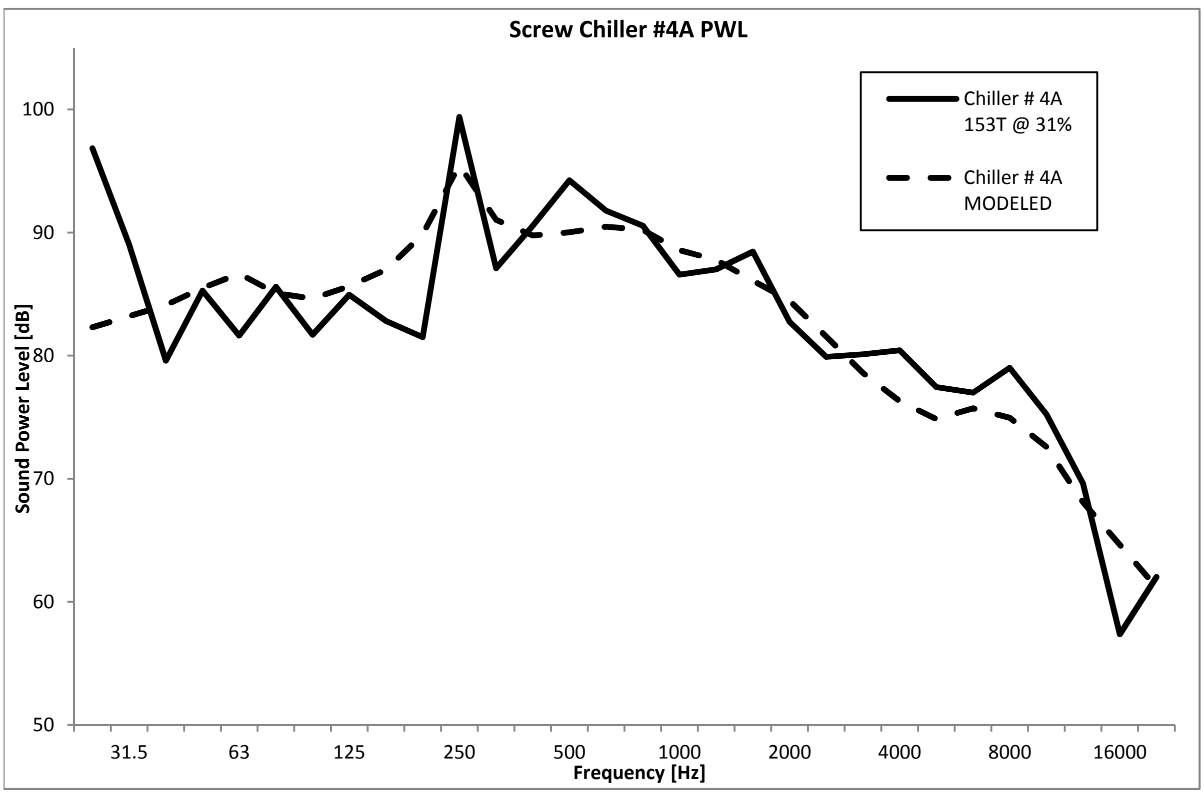


Figure A-14: Measurement Results for Screw Chiller #4A

4B

Location 901 W 38th	Test Date 9 SEP 2016
Address	Contact Glenn Harcrow Steve

Manufacturer CARRIER	Model 30GXN153	# Comps 2	# Fans 10	Temp 94 °F
Capacity 153 Tons	Oper. Pt. 68 %	RPM	Inst. Date 2013	V_{wind} 110 fpm
kW [0-60] Hz	LxDxH 231"x85"x80" ~~ft~~	SPL$_{10'}$ dBA	f_c Hz	
~~Top:~~ d_1 14 in LONG	d_2 56 in	~~Side:~~ d_1 12 in SHORT	d_2 32 in	Cal. @ 94 / 114 dB

NOTES

DIMENSIONED SKETCH

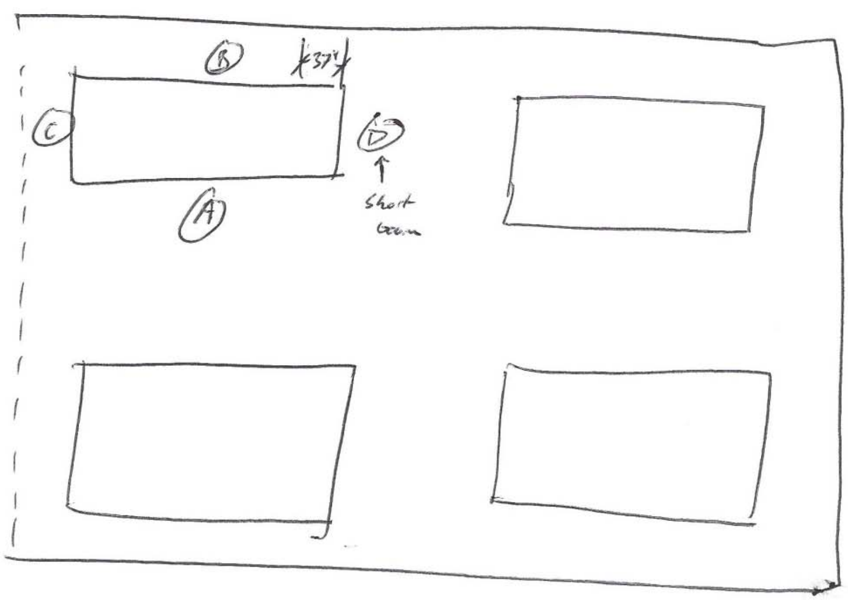


Figure A-15: Site Data Sheet for Screw Chiller #4B

Table A-8: Measurement Results for Screw Chiller #4B

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	--	--	--	85.2	83.9	83.3	83.0	83.6	82.5	82.9
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	93.6	87.1	87.5	93.4	91.4	90.3	88.0	86.9	90.0	84.7
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	80.7	81.4	81.1	78.9	77.5	78.5	73.8	69.5	62.4	56.8
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	101.0	98.4	100.9	25.7	0.654					

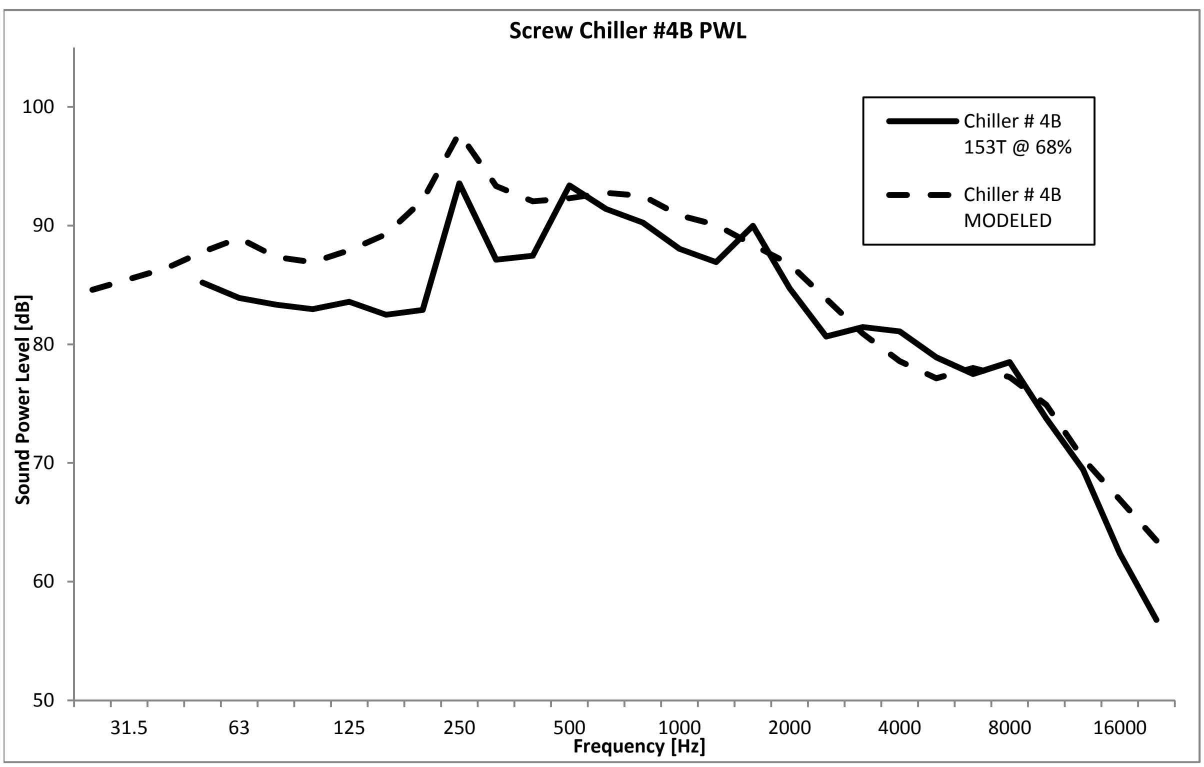


Figure A-16: Measurement Results for Screw Chiller #4B

5

Location 901 W 38th #2				Test Date 14 Apr 2016		
				Contact Glenn Harcrow Steve		
Address						
Manufacturer Carrier	Model 30GXN163		# Comps 2	# Fans 12	Temp 81 °F	
Capacity 163 Tons	Oper. Pt. 31 %	RPM	Inst. Date 2013		V_{wind} 140 fpm	
kW [0-60] Hz	LxDxH 267"x85"x80" ~~ft~~		SPL$_{10'}$ dBA	f_c Hz		
Top: d_1 ~~in~~	~~d_2~~ in	Side: d_1 11.75 in	d_2 38.75 in		Cal. @ 94 / 114 dB	

NOTES

DIMENSIONED SKETCH

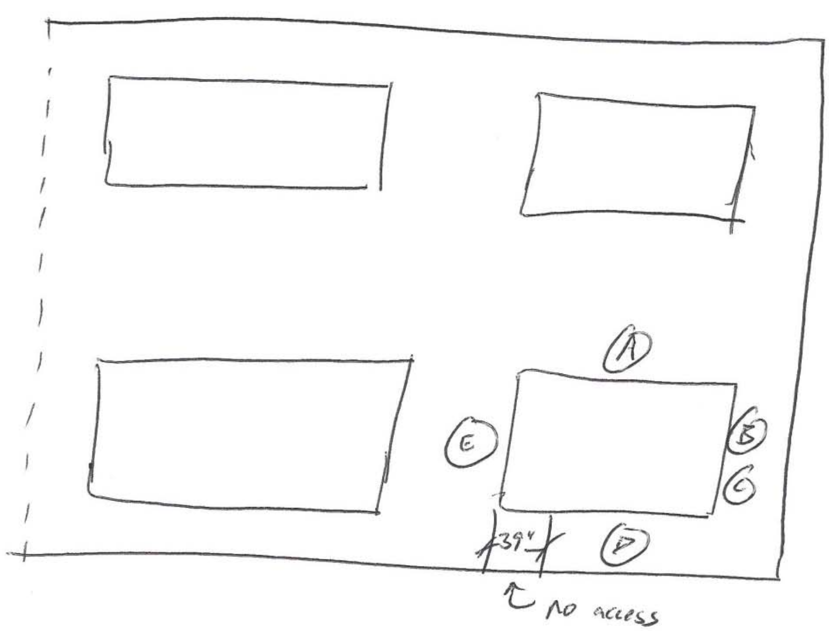


Figure A-17: Site Data Sheet for Screw Chiller #5

Table A-9: Measurement Results for Screw Chiller #5

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	--	--	--	89.2	85.4	83.7	78.3	85.9	86.9	87.5
`										
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	101.3	91.6	90.8	93.8	90.1	94.9	91.4	84.3	91.1	86.1
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	84.5	86.2	84.3	80.1	83.6	82.1	80.9	76.9	70.9	65.4
Freq [Hz]	**dB**	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	104.9	101.2	104.7	26.6	0.599					

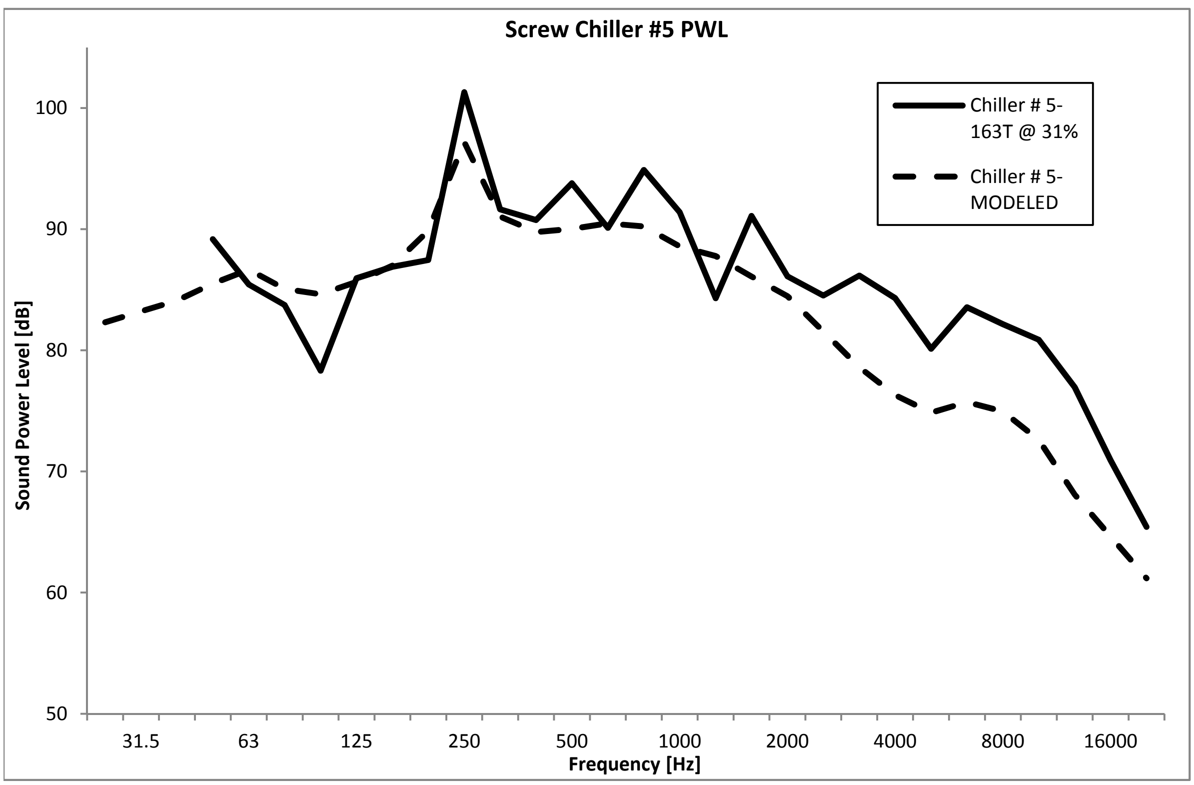


Figure A-18: Measurement Results for Screw Chiller #5

6

Location 901 W 38th #3					Test Date 9 Sep 2016		
Address					Contact Glen Harcrow		
Manufacturer		Model		# Comps 2		# Fans 12	Temp 94 °F
Capacity 163 Tons	Oper. Pt. 70 %		RPM	Inst. Date 2013			V_{wind} 110 fpm
kW [0-60] Hz	LxDxH 267"x 83"x80" ft			$SPL_{10'}$ dBA		f_c Hz	
Top: d_1 14 in	d_2 56 in	Side: d_1 12 in	d_2 32 in			Cal. @ 94 / 114 dB	

NOTES

DIMENSIONED SKETCH

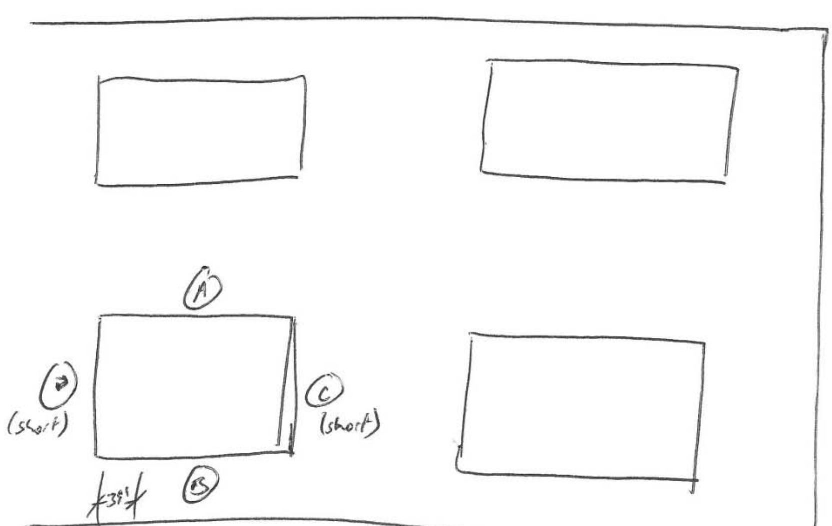


Figure A-19: Site Data Sheet for Screw Chiller #6

Table A-10: Measurement Results for Screw Chiller #6

Freq [Hz]	25	31.5	40	50	63	80	100	125	160	200
PWL [dB]	85.4	85.4	85.6	91.3	87.4	85.2	81.0	86.7	88.1	89.4
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	97.2	94.0	90.5	94.4	94.4	94.5	93.3	85.5	94.0	85.1
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	83.2	84.7	83.0	78.4	80.4	80.0	77.4	72.7	69.4	68.1
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	104.5	101.6	104.3	27.0	0.719					

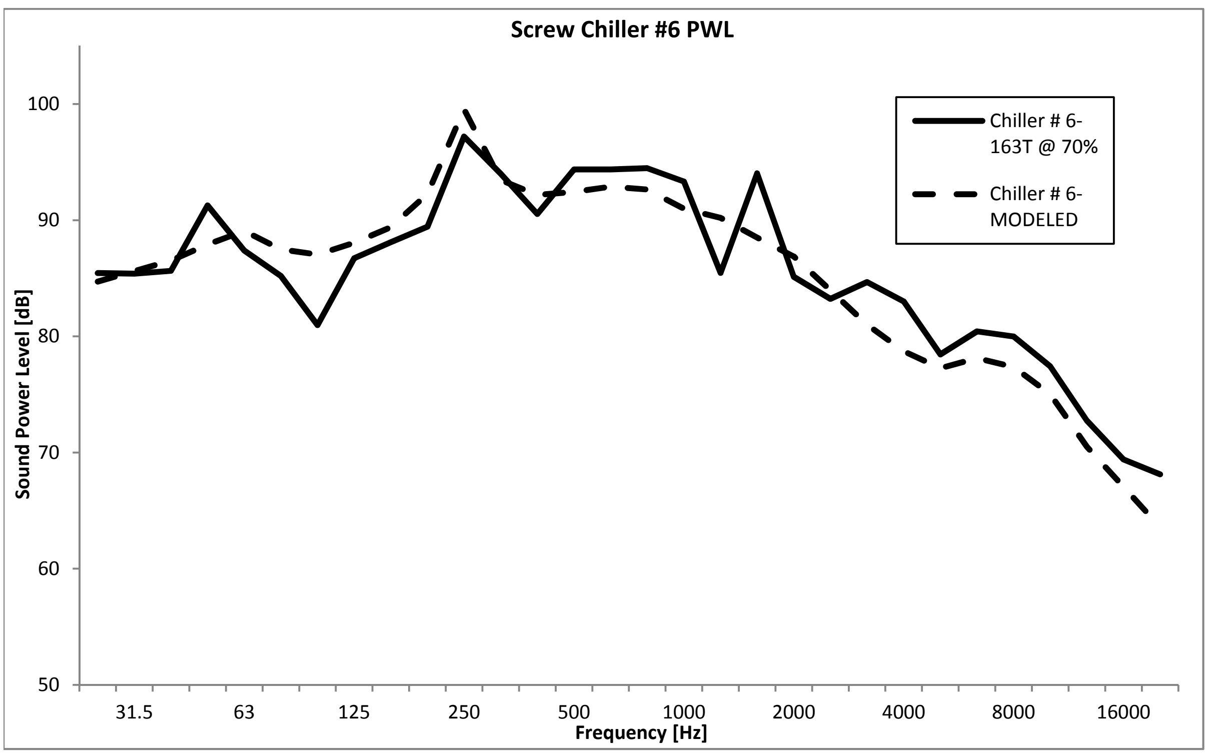


Figure A-20: Measurement Results for Screw Chiller #6

7A

Location: MEXICAN AMERICAN CULTURAL CENTER	Test Date: 22 April 2016
Address: RANEY ST.	Contact: HERLINDA ZAMORA

Manufacturer: TRANE	Model: RTAA0804	# Comps: 2	# Fans: 8	Temp: 93 °F
Capacity: 80 Tons	Oper. Pt.: 52 %	RPM	Inst. Date: 2007	V_{wind}: 110 fpm
kW [0-60] Hz	LxDxH: 211" x 112" x 85" ft	$SPL_{10'}$ dBA		f_c: 592 Hz
Top: d_1 in, d_2 in	Side: d_1: 12 in	d_2: 39 in		Cal. @ 94 / 114 dB

NOTES

Ivie #687

Compressor Blankets & shrouds around fans

DIMENSIONED SKETCH

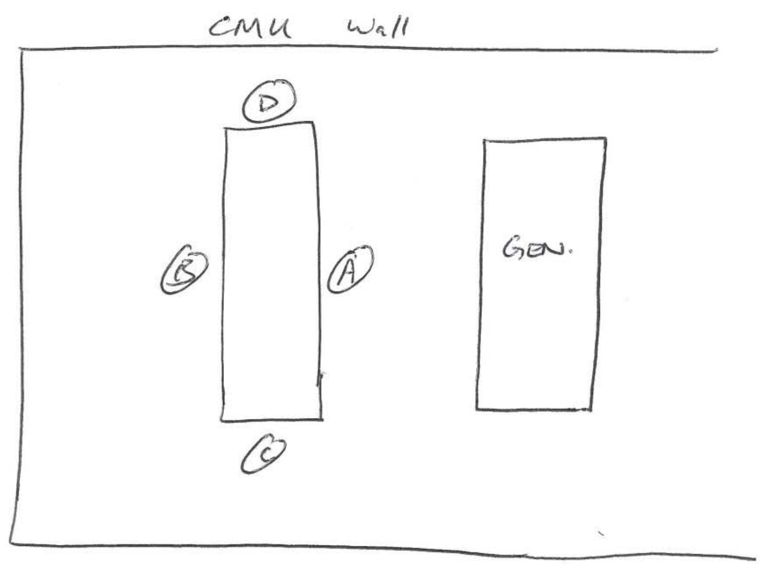


Figure A-21: Site Data Sheet for Screw Chiller #7A

Table A-11: Measurement Results for Screw Chiller #7A

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	74.9	74.7	75.0	70.6	74.1	76.4	78.2	80.3	78.7	83.0
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	82.1	79.7	81.4	79.7	79.8	84.8	78.5	78.7	79.2	70.5
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	73.7	71.0	67.2	61.4	56.1	59.3	56.9	50.1	52.8	51.7
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	92.3	89.3	92.2	22.6	0.142					

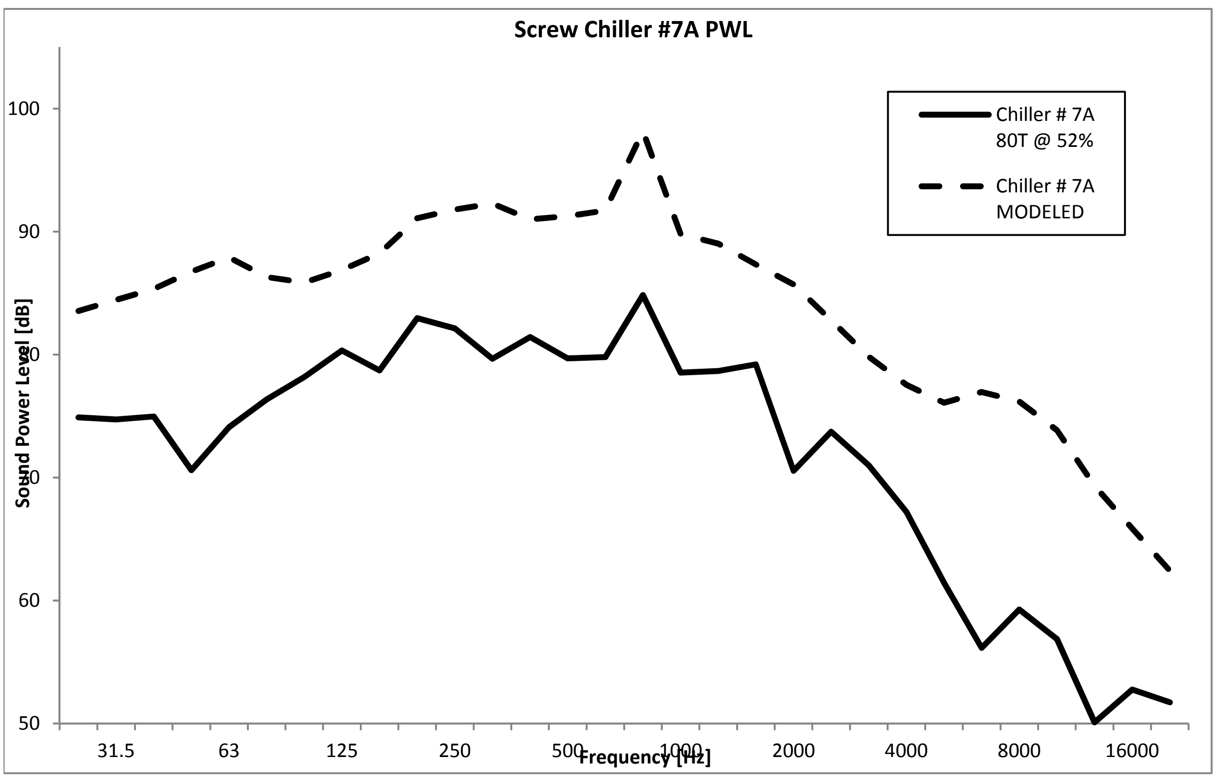


Figure A-22: Measurement Results for Screw Chiller #7A

7B

Location MACC					Test Date 21 Jul 2016		
Address					Contact Herlinda Zamora Rigoberto		
Manufacturer TRANE		Model RTAA0804		# Comps 2		# Fans 8	Temp 96 °F
Capacity 80 Tons	Oper. Pt. 72 %		RPM	Inst. Date 2007			V_{wind} 130 fpm
kW [0-60] Hz	LxDxH 211"x112"x85" ft			$SPL_{10'}$ dBA		f_c 592 Hz	
Top: d_1 in	d_2 in	Side: d_1 9.75 in		d_2 32.5 in			Cal. @ 94 / 114 dB

NOTES

Ivie #1

DIMENSIONED SKETCH

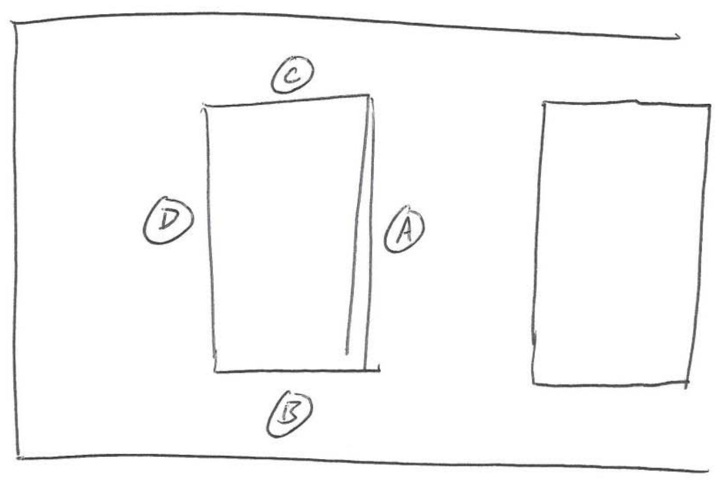


Figure A-23: Site Data Sheet for Screw Chiller #7B

Table A-12: Measurement Results for Screw Chiller #7B

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	78.9	78.7	80.0	73.8	76.2	76.7	82.0	83.1	81.3	84.6
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	80.3	79.2	82.4	82.1	81.7	85.8	77.6	76.0	78.0	72.8
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	74.6	71.8	67.5	64.2	65.0	65.1	63.0	56.1	56.1	55.4
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	93.4	89.9	93.3	22.8	0.153					

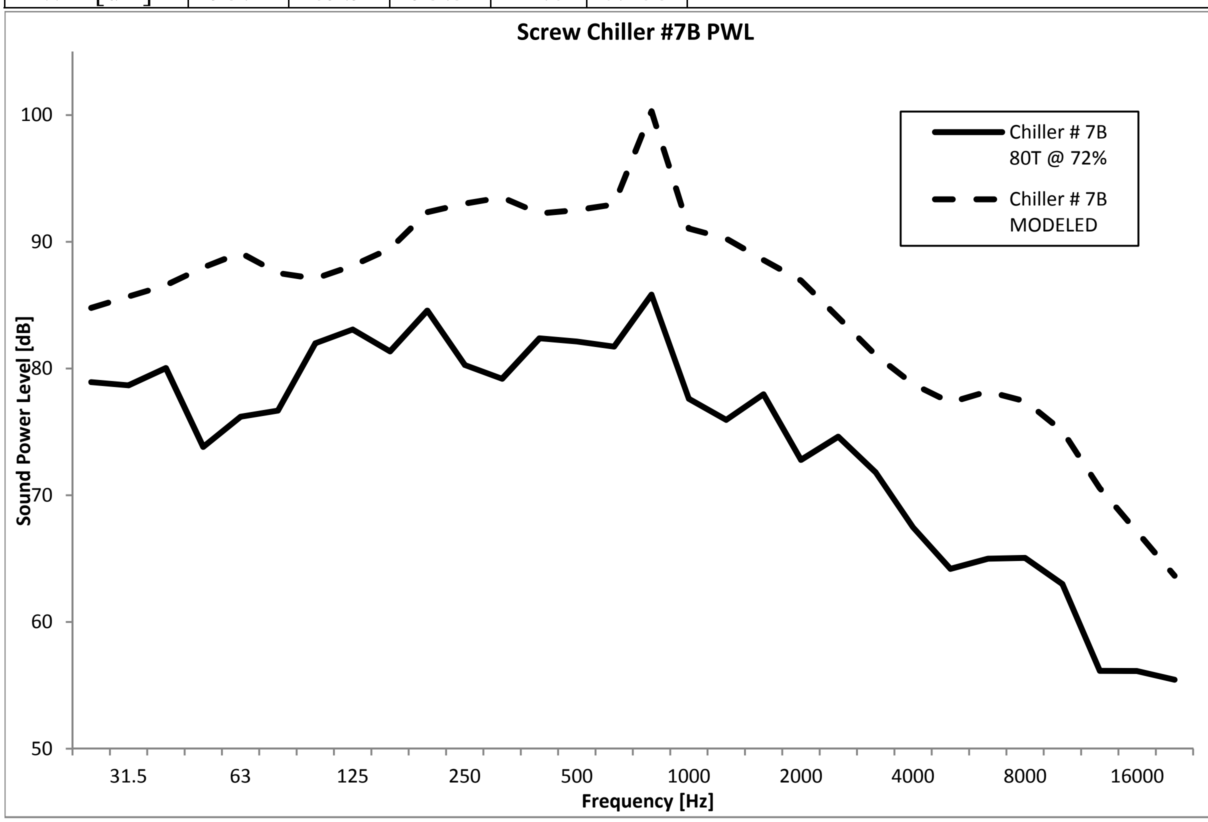


Figure A-24: Measurement Results for Screw Chiller #7B

8A

Location: ACC HIGHLAND CAMPUS	Test Date: 10 MAY 2016
Address:	Contact: DEAN JOHNSON

Manufacturer: YORK	Model: YVAA0248	# Comps: 1	# Fans: —	Temp: 88 °F
Capacity: 248 Tons	Oper. Pt.: 77 %	RPM:	Inst. Date: 2013	V_{wind}: — fpm
kW [0-60]: Hz	LxDxH: 126" x 70" x 91" ft	SPL$_{10'}$: dBA	f_c: 689 Hz	
Top: d_1: — in	d_2: — in	Side: d_1: 10 in	d_2: 37 in	Cal. @ 94 / 114 dB

NOTES

IVIE #1

DIMENSIONED SKETCH

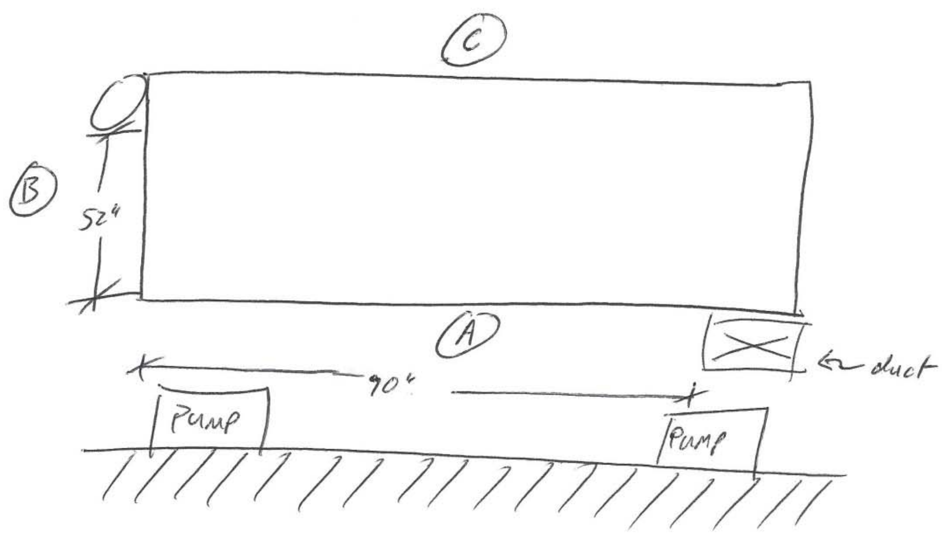


Figure A-25: Site Data Sheet for Screw Chiller #8A

Table A-13: Measurement Results for Screw Chiller #8A

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	76.3	76.6	--	--	84.3	91.8	77.5	83.3	93.5	79.8
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	81.8	83.7	84.4	83.9	86.4	95.8	90.0	83.4	86.0	87.2
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	95.1	89.8	87.2	89.7	85.1	88.3	85.5	78.9	75.0	68.3
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	102.3	101.8	101.9	27.9	0.329					

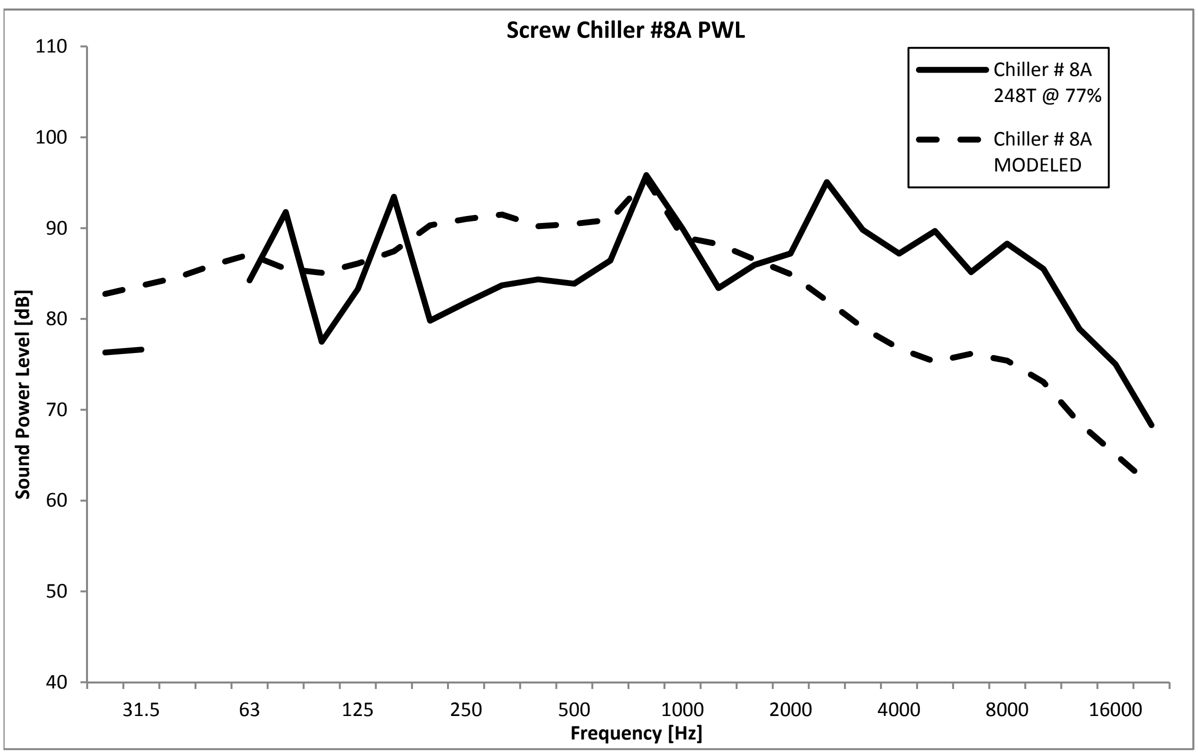


Figure A-26: Measurement Results for Screw Chiller #8A

8B

Location ACC HIGHLAND	Test Date 21 Jul 2016
Address	Contact DEAN JOHNSON

Manufacturer YORK	Model YVAA 0248	# Comps 1	# Fans —	Temp 102 °F
Capacity 248 Tons	Oper. Pt. 91 %	RPM	Inst. Date 2013	V_{wind} — fpm
kW [0-60] Hz	LxDxH 126" x 70" x 91" ft	$SPL_{10'}$ dBA	f_c 247 Hz	
Top: d_1 — in	d_2 — in	Side: d_1 9.75 in	d_2 32.5 in	Cal. @ 94 / 114 dB

NOTES

IVIE #3

DIMENSIONED SKETCH

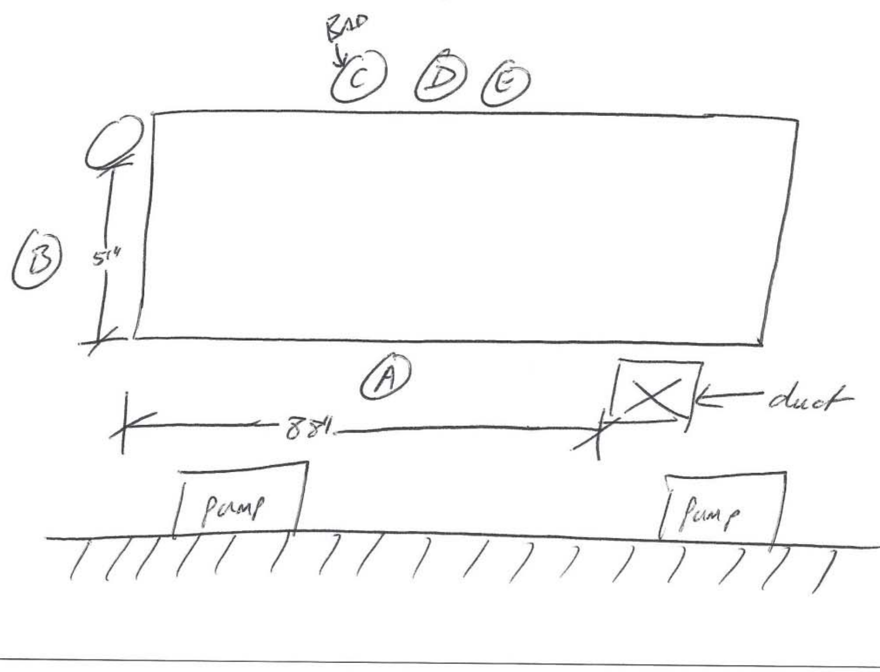


Figure A-27: Site Data Sheet for Screw Chiller #8B

Table A-14: Measurement Results for Screw Chiller #8B

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	77.0	74.4	--	65.9	80.4	92.9	82.0	86.1	96.5	90.3
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	90.8	89.1	82.3	84.7	84.9	89.4	87.6	83.7	84.5	89.1
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	90.1	81.6	80.1	87.1	83.2	86.0	83.4	75.0	69.9	72.7
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	102.1	98.4	101.8	26.8	0.411					

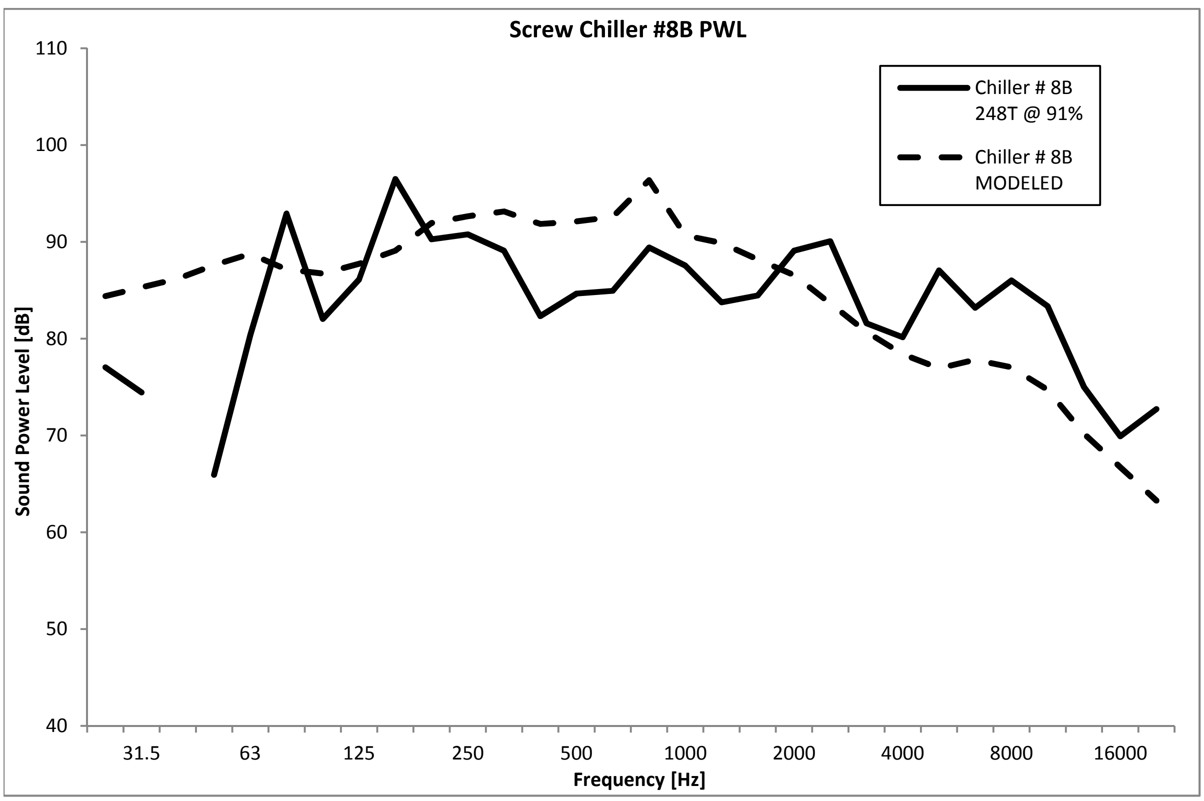


Figure A-28: Measurement Results for Screw Chiller #8B

9A

Location ROUND ROCK HS #1	Test Date 17 MAY 2016
Address	Contact GLEN TONY

Manufacturer TRANE	Model RTHC 182	# Comps 1	# Fans —	Temp 79 °F
Capacity 170 Tons	Oper. Pt. 72 %	RPM	Inst. Date	V_{wind} — fpm
kW [0-60] Hz	LxDxH 148" x 45" x 80" ft	$SPL_{10'}$ dBA	f_c 301 Hz	
Top: d_1 — in	d_2 — in	Side: d_1 10 in	d_2 37 in	Cal. @ 94 / 114 dB

NOTES

IVIE # 2

DIMENSIONED SKETCH

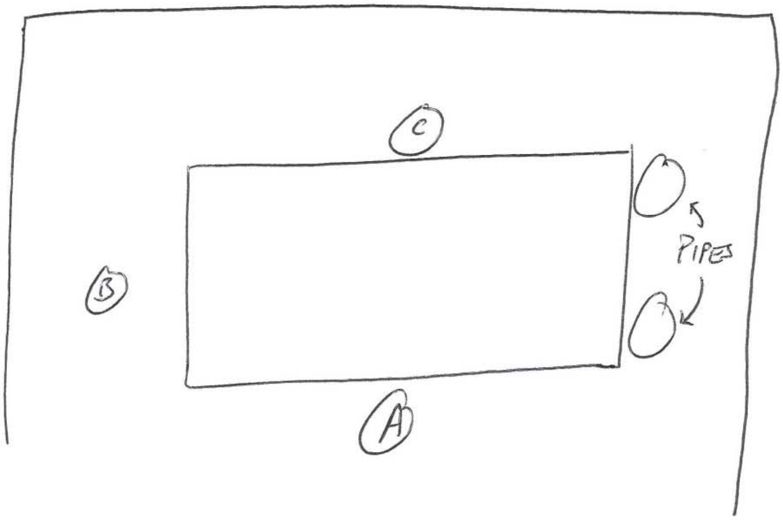


Figure A-29: Site Data Sheet for Screw Chiller #9A

Table A-15: Measurement Results for Screw Chiller #9A

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	82.1	83.5	85.7	82.2	78.2	80.8	77.9	78.9	90.1	86.2
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	87.9	84.8	94.0	88.7	88.7	101.4	91.2	90.9	91.1	86.0
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	83.5	78.8	78.6	78.4	77.6	74.6	69.6	65.4	62.2	54.3
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	104.0	103.3	104.0	31.6	0.680					

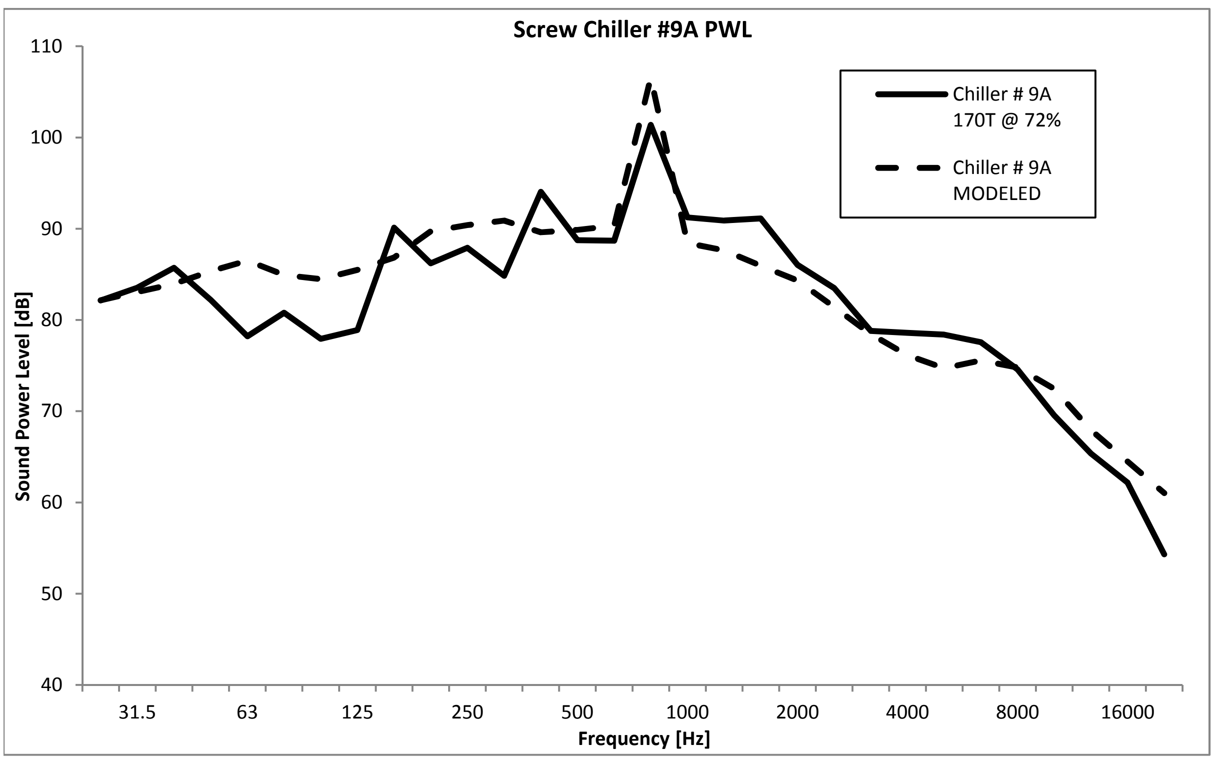


Figure A-30: Measurement Results for Screw Chiller #9A

(9B)

Location: ROUND ROCK HS #1a	Test Date: 17 MAY 2016
Address:	Contact: Glenn, Tony

Manufacturer: TRANE	Model: RTHC 182	# Comps	# Fans: ~~—~~	Temp 79 °F
Capacity 170 Tons	Oper. Pt. 46 %	RPM	Inst. Date	V_{wind} ~~—~~ fpm
kW [0-60] Hz	LxDxH 148" x 45" x 80 ft	$SPL_{10'}$ dBA		f_c Hz
Top: d_1 ~~—~~ in	d_2 ~~—~~ in	Side: d_1 10 in	d_2 37 in	Cal. @ 94 / 114 dB

NOTES

UNIT was forced
to 46%

DIMENSIONED SKETCH

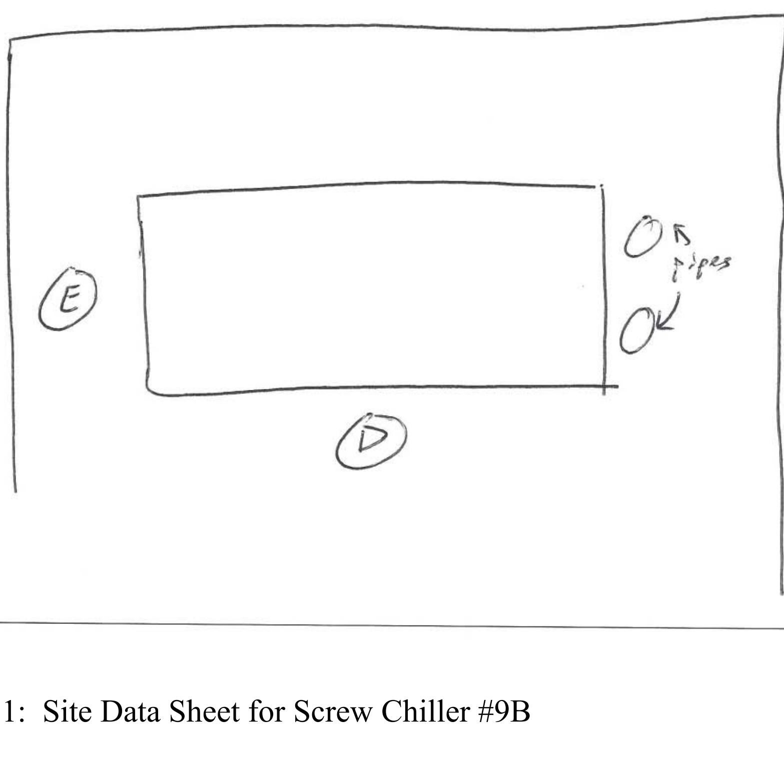


Figure A-31: Site Data Sheet for Screw Chiller #9B

Table A-16: Measurement Results for Screw Chiller #9B

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	87.0	88.4	90.4	87.3	83.6	85.9	82.7	86.3	95.5	89.8
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	94.3	91.6	102.9	95.2	95.6	108.3	100.6	105.2	107.1	104.0
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	107.4	99.3	103.4	103.2	99.8	94.9	89.0	80.2	71.8	62.6
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	115.4	115.7	115.1	31.6	0.003					

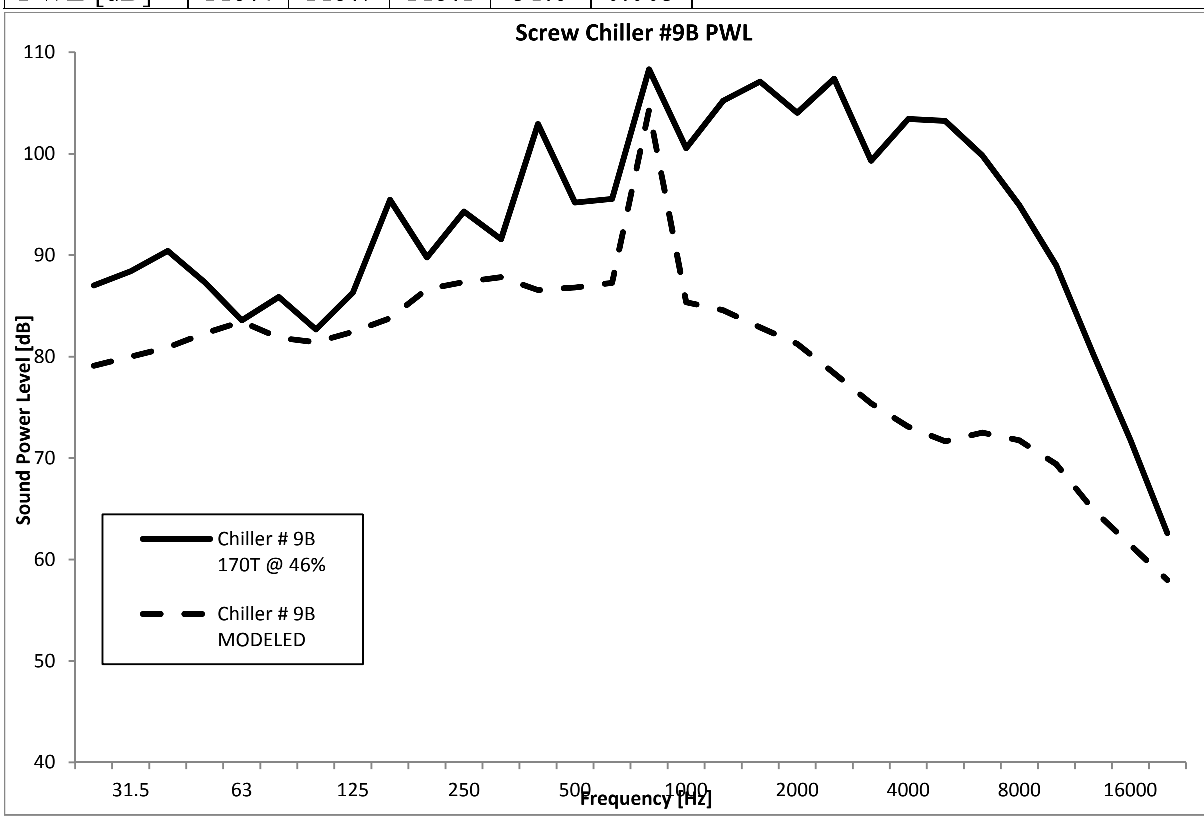


Figure A-32: Measurement Results for Screw Chiller #9B

10A

Location: ROUND ROCK HS #2			Test Date: 17 MAY 2016		
Address			Contact: GLEN TONY		
Manufacturer: TRANE	Model: RTHC 182	# Comps: 1	# Fans: —	Temp: 79 °F	
Capacity: 170 Tons	Oper. Pt.: 61 %	RPM	Inst. Date	V_{wind}: — fpm	
kW [0-60] Hz	LxDxH: 148" x 45" x 80" ~~ft~~	SPL$_{10'}$ dBA	f_c: 592 Hz		
Top: d_1 in	d_2 in	Side: d_1 10 in	d_2 37 in		Cal. @ 94 / 114 dB

NOTES

IVIE #3

DIMENSIONED SKETCH

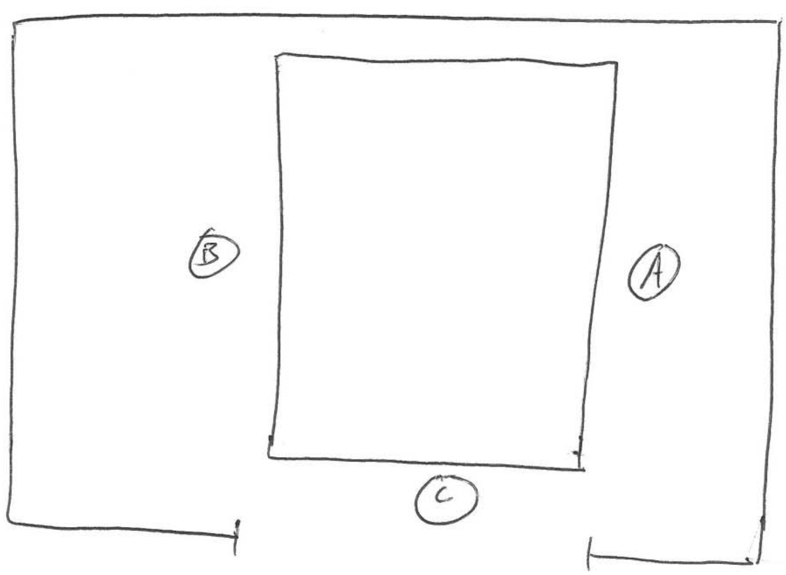


Figure A-33: Site Data Sheet for Screw Chiller #10A

Table A-17: Measurement Results for Screw Chiller #10A

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	77.1	81.9	78.4	64.6	76.9	82.5	76.8	72.1	86.4	74.9
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	87.2	82.5	97.7	79.2	94.9	108.0	83.9	86.3	92.2	86.5
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	82.6	79.6	77.7	77.4	77.7	76.9	74.4	73.0	65.3	--
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	108.8	108.5	108.8	28.2	0.466					

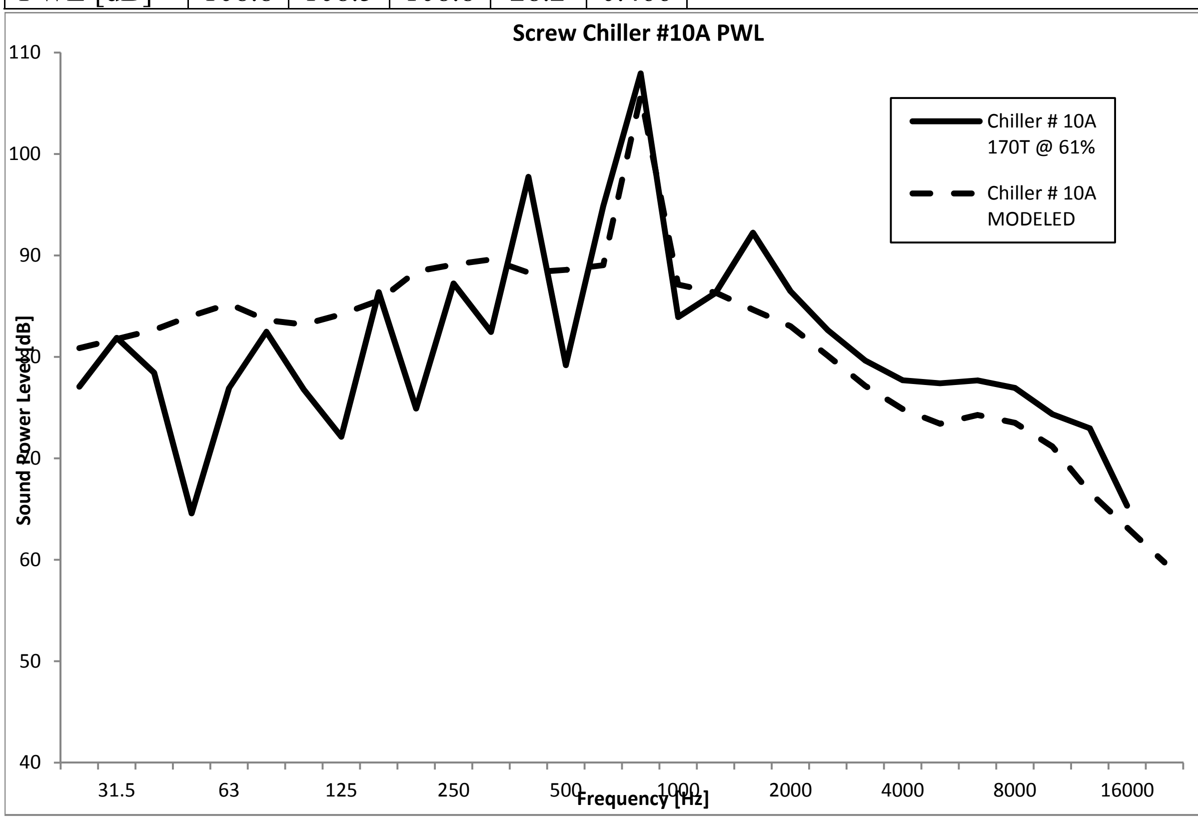


Figure A-34: Measurement Results for Screw Chiller #10A

9C

Location ROUND ROCK HS #1			Test Date 12 SEP 2016		
Address			Contact Glen Tony		
Manufacturer TRANE	Model RTHC 182		# Comps 1	# Fans —	Temp 93 °F
Capacity 170 Tons	Oper. Pt. 72 %	RPM	Inst. Date		V_{wind} — fpm
kW [0-60] Hz	LxDxH 148"x45"x80" ft		$SPL_{10'}$ dBA		f_c 893 Hz
Top: d_1 in	d_2 in	Side: d_1 10 in	d_2 37 in		Cal. @ 94 / 114 dB

NOTES

IVIE #7

DIMENSIONED SKETCH

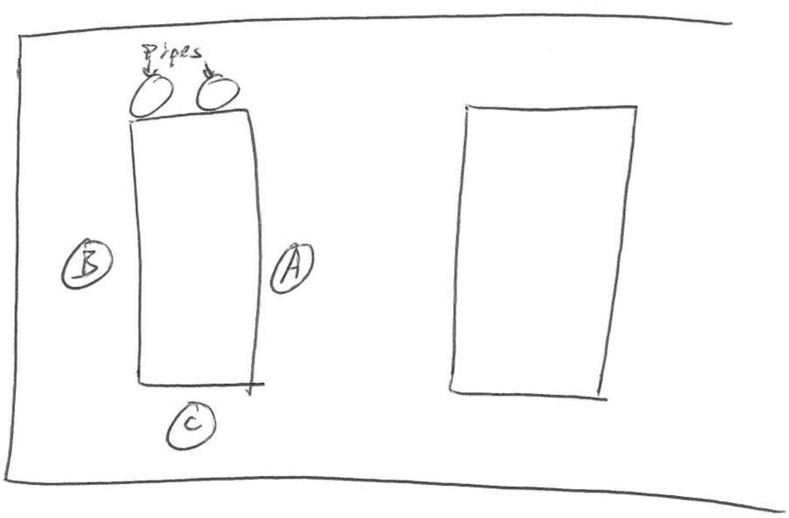


Figure A-35: Site Data Sheet for Screw Chiller #9C

Table A-18: Measurement Results for Screw Chiller #9C

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	83.2	85.6	88.9	82.1	80.2	88.0	73.9	75.9	90.7	83.4
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	89.4	83.8	95.3	87.6	90.2	103.7	91.9	90.5	89.9	86.5
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	85.0	79.7	79.5	79.6	78.5	75.4	70.8	67.1	65.1	58.7
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	107.2	105.6	107.1	27.3	0.554					

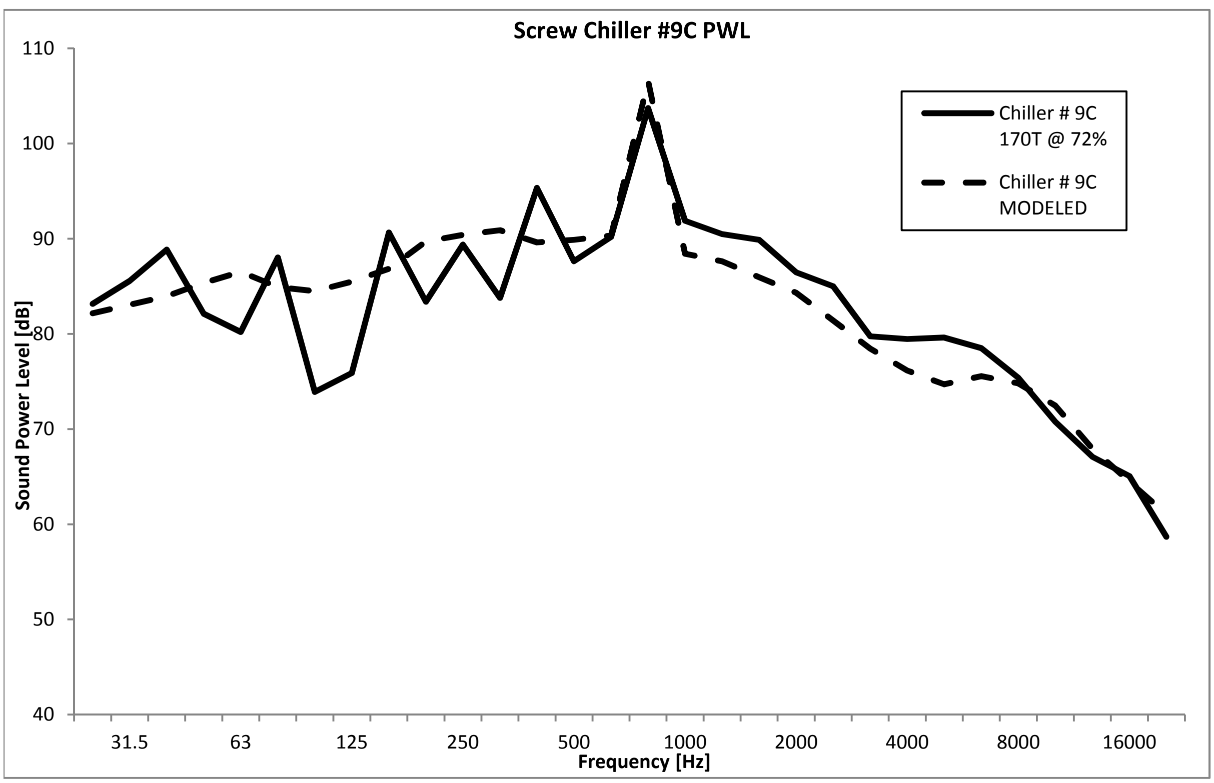


Figure A-36: Measurement Results for Screw Chiller #9C

11

Location ROUND ROCK HS #3	Test Date 12 SEPT 2016
Address	Contact Glen Tony

Manufacturer TRANE	Model RTHC182	# Comps 1	# Fans ~~1~~	Temp 93 °F
Capacity 170 Tons	Oper. Pt. 69 %	RPM	Inst. Date	V_{wind} — fpm
kW [0-60] Hz	LxDxH 148"x45"x 80" ft		$SPL_{10'}$ dBA	f_c 592 Hz
Top: d_1 — in	~~d_2~~ in	Side: d_1 10 in	d_2 37 in	Cal. @ 94 / 114 dB

NOTES

IVIE # 8

DIMENSIONED SKETCH

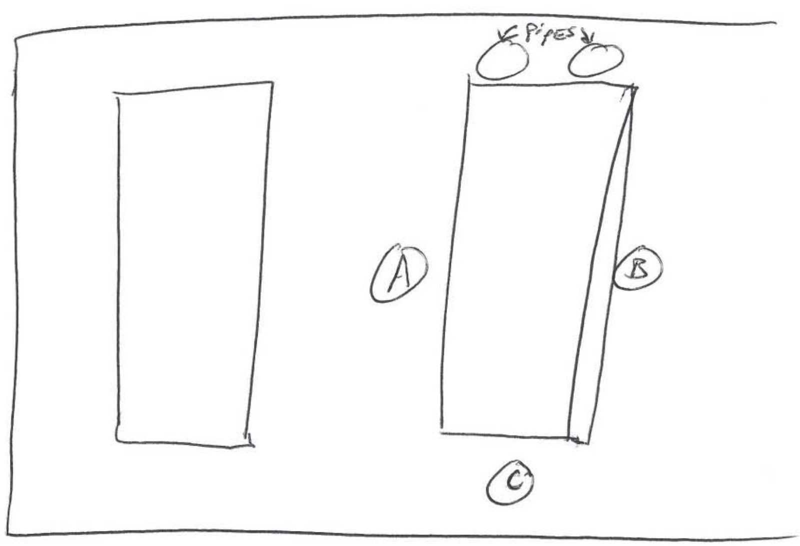


Figure A-37: Site Data Sheet for Screw Chiller #11

Table A-19: Measurement Results for Screw Chiller #11

Freq [Hz]	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
PWL [dB]	74.0	78.9	80.8	76.4	76.8	82.2	78.9	74.4	84.9	76.3
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	85.4	78.7	89.1	77.6	88.2	104.7	87.2	88.6	88.9	84.1
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	80.6	75.9	72.4	70.9	72.0	73.1	70.5	69.6	63.3	56.1
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	105.4	105.2	105.4	27.2	0.691					

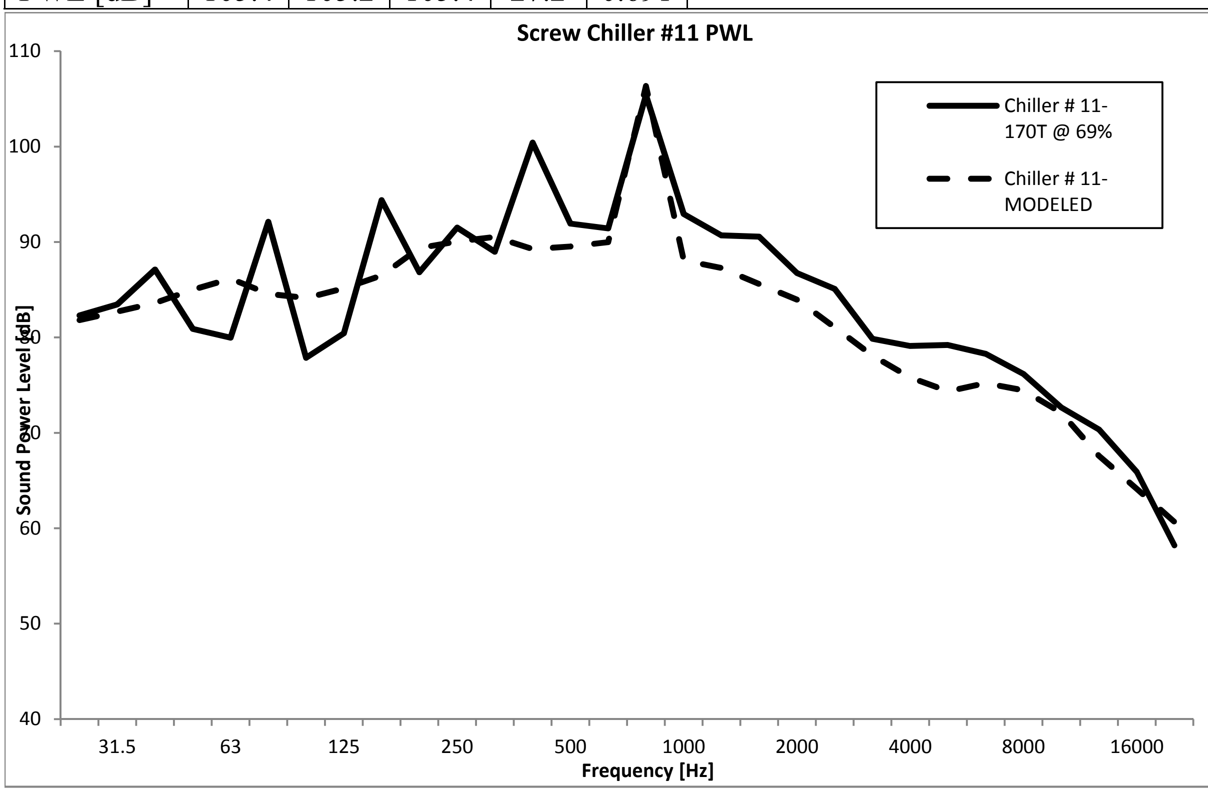


Figure A-38: Measurement Results for Screw Chiller #11

(10B)

Location ROUND ROCK HS # 2	Test Date 12 SEPT 2016
Address	Contact Glen Tony

Manufacturer TRANE	Model RTHC 182	# Comps 1	# Fans —	Temp 93 °F

Capacity 170 Tons	Oper. Pt. 68 %	RPM	Inst. Date	V_{wind} — fpm
kW [0-60] Hz	LxDxH 148" x 45" x 80" ft	$SPL_{10'}$ dBA		f_c 592 Hz

Top: d_1 in	d_2 in	Side: d_1 14 in	d_2 56 in		Cal. @ 94 / 114 dB

NOTES

IVIE # 9

DIMENSIONED SKETCH

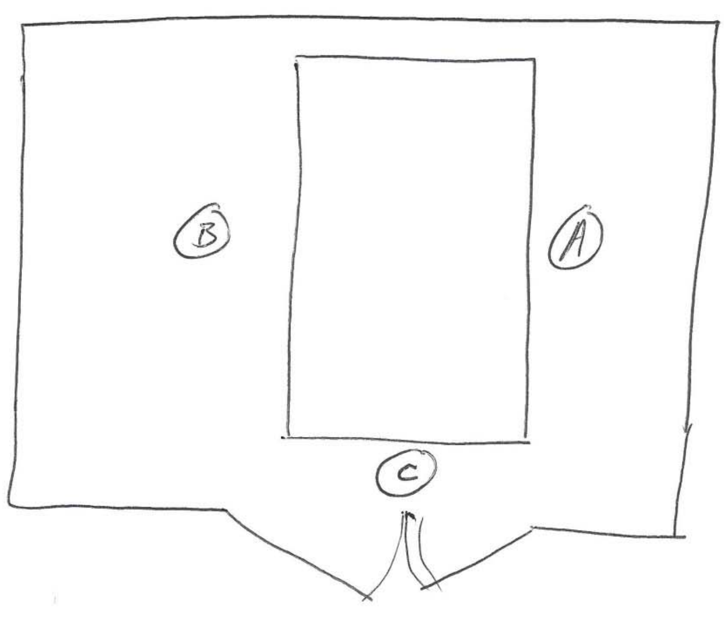


Figure A-39: Site Data Sheet for Screw Chiller #10B

Table A-20: Measurement Results for Screw Chiller #10B

Freq [Hz]	25	31.5	40	50	63	80	100	125	160	200
PWL [dB]	82.3	83.5	87.1	80.9	80.0	92.1	77.9	80.4	94.4	86.8
Freq [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**
PWL [dB]	91.5	89.0	100.4	91.9	91.4	105.4	92.9	90.7	90.6	86.7
Freq [Hz]	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**	**16000**	**20000**
PWL [dB]	85.1	79.9	79.1	79.2	78.3	76.2	72.7	70.3	65.9	58.2
	dB	**dBA**	**dBC**	**SQI**	**R^2**					
PWL [dB]	107.9	106.8	107.8	27.8	0.641					

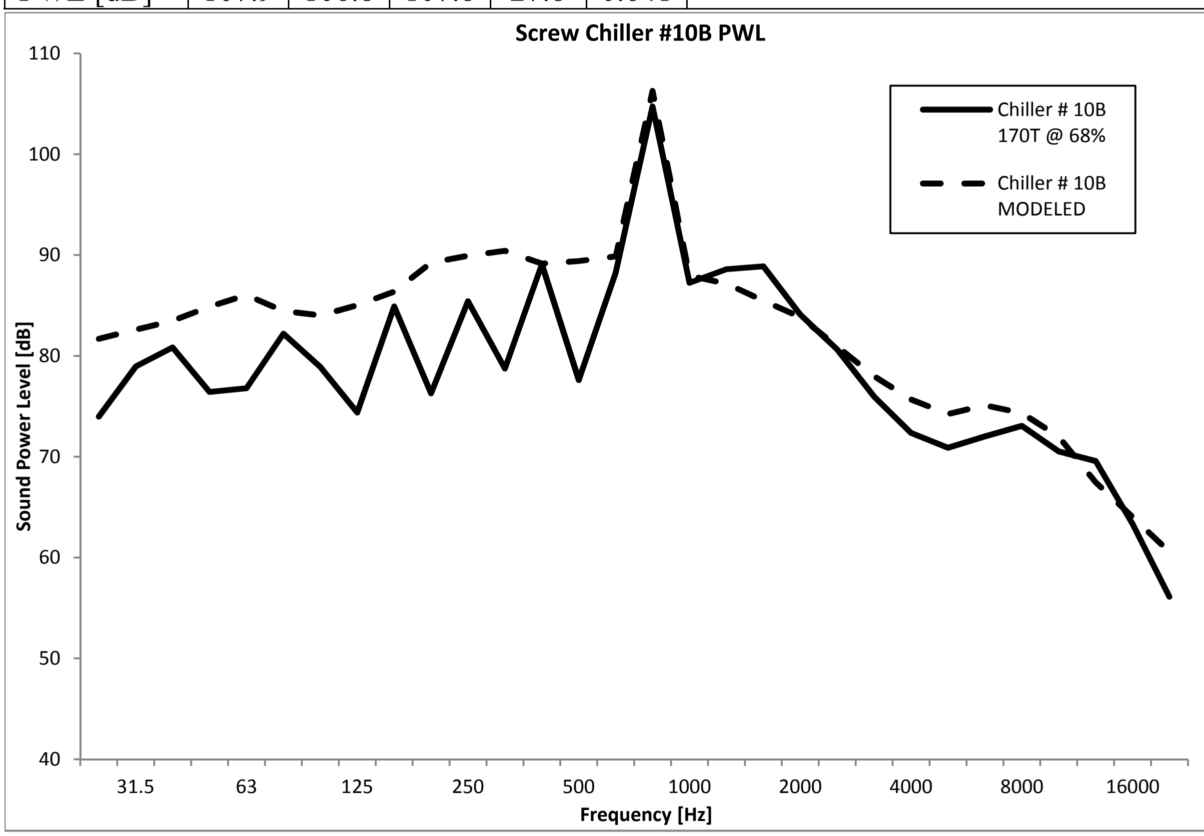


Figure A-40: Measurement Results for Screw Chiller #10B

Table A-21: Octave-Band Level PWL Data

#	ID		31.5	63	125	250	500	1000	2000	4000	8000	16000
1	1A		--	77.4	81.0	77.5	82.8	95.9	90.3	81.8	73.1	70.7
14	1B		78.3	91.2	85.8	84.2	88.1	100.0	93.0	84.5	77.1	75.3
2	2A		--	--	95.8	96.5	98.3	96.1	89.2	79.2	80.4	67.7
17	2B		--	102.8	98.1	97.8	99.8	97.3	90.9	82.1	78.2	68.9
3	3A		--	98.6	94.4	94.4	93.0	93.6	90.4	78.1	80.2	73.2
12	3B		88.8	96.5	98.9	101.8	96.9	94.9	92.3	79.5	80.1	71.1
4	4A		97.6	89.3	88.1	99.7	97.2	93.2	89.9	84.3	82.1	70.5
5	4B		--	89.0	87.8	94.7	96.1	93.4	91.5	85.4	81.8	70.4
15	5-		--	91.5	89.8	101.9	96.6	96.7	93.0	89.0	87.1	78.2
16	6-		90.3	93.5	90.9	99.4	98.2	97.2	94.9	87.5	84.2	75.3
6	7A		79.6	79.1	83.9	86.6	85.1	86.5	80.7	72.8	62.4	56.4
11	7B		84.0	80.5	87.0	86.8	86.9	86.8	80.4	73.7	69.2	60.7
7	8A		--	--	94.0	86.8	89.8	97.0	96.2	93.8	91.3	80.7
13	8B		--	93.2	97.0	94.9	88.9	92.3	93.2	88.8	89.2	77.8
8	9A		88.8	85.5	90.7	91.3	96.0	102.1	92.8	83.4	79.8	67.3
9	9B		93.6	90.6	96.2	97.1	104.2	110.5	111.2	107.1	101.3	80.9
10	9C		91.3	89.6	90.9	91.2	97.0	104.2	92.4	84.4	80.7	69.6
18	10A		84.4	83.6	87.0	88.7	99.6	108.0	93.6	83.1	81.3	--
19	10B		83.5	84.1	86.2	86.7	91.9	104.9	90.6	78.4	76.8	70.7
20	11-		89.6	92.7	94.7	94.3	101.4	105.8	92.9	84.2	81.0	71.9

Appendix B: Data Processing Application Details

Audio was recorded as 44.1 kHz, 16-bit audio files using Presonus Studio One software, along with the hardware discussed in Chapter 2. At each site, calibration files were recorded for each microphone at microphone pre-amplifier gain settings that were then left unchanged throughout the session. Recordings were then made of each accessible side of the chiller. The calibration and constituent surfaces recording files appear as waveforms in the StudioOne user interface; these, along with the gain control and metering sections are shown in Figure B-1.

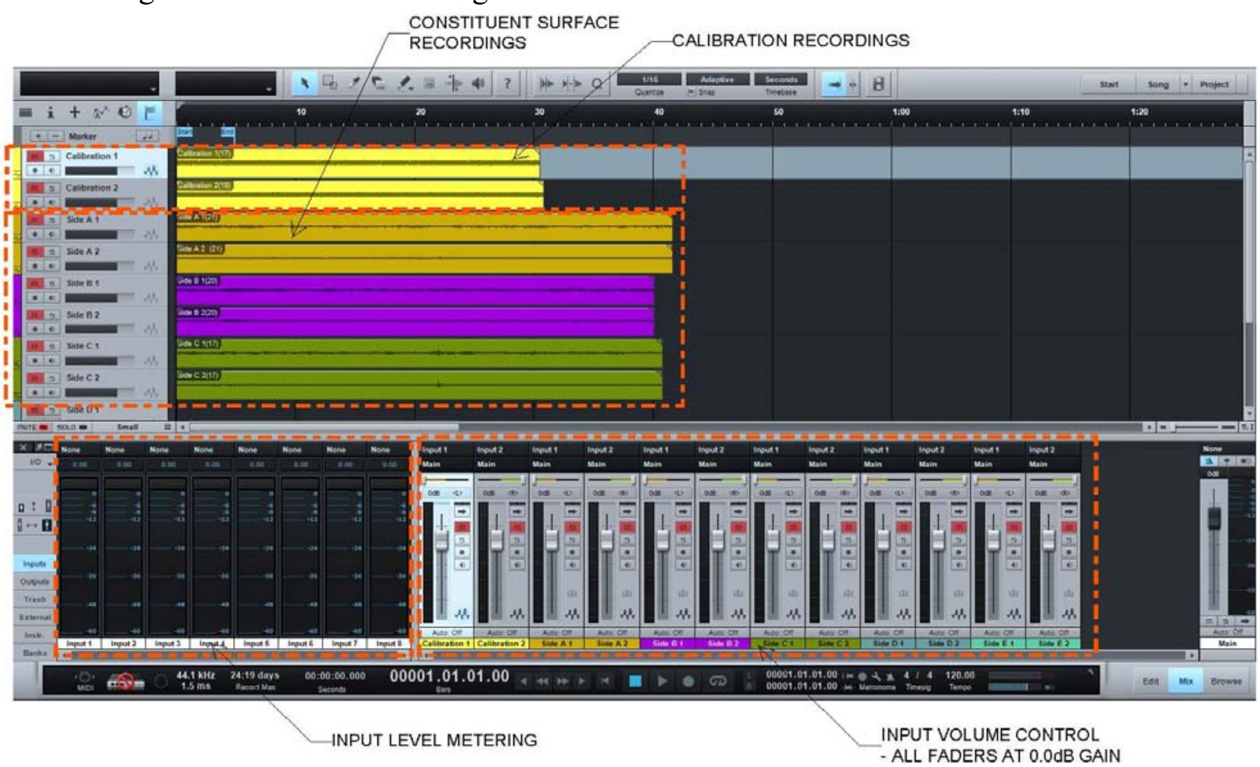


Figure B-1: Typical audio recording interface using the Presonus StudioOne application.

The audio files were converted to stereo WAV files within the StudioOne software, and were then imported into the custom-made data processing application based on the National Instruments LabView platform. A separate WAV file was created for the calibration files and each of the constituent sides, with the inner surface recording on the stereo-left channel, and the outer surface recording on the stereo-right channel. The file path to each WAV file, is selected and displayed at the top-left of the LabView interface (refer to Figure B-2), with the calculated output level in mV RMS for each microphone when ensonified by the calibrator at the pre-amplifier settings used for the measurements (recorded as the calibration file) displayed in the middle left, and the output file path selected and displayed at the bottom left. Up to five constituent surfaces can be processed at a time, as long as a single pair of calibration files applies to them all – in other words, the microphone pre-amplifier gain settings and relative microphone position must be the same for all measurements processed in a given batch. Waveforms for all selected measurement files are displayed in individual charts at the right side of the LabView interface. The audio channel settings are set and displayed in the center section of the interface. These channel settings include, for each channel:

- the time of each recording in seconds,
- the dB reference value – set to 20×10^{-4} Pa,
- the pregain – set at null, and
- a frequency weighting filter – set to linear.

With the input and output files selected and the appropriate channel settings applied, the LabView application is run. A signal flow diagram of the LabView application is shown in Figure B-3. The inner and outer surface microphone calibration files are extracted and the RMS voltages of the calibration recordings are measured within the Audio Signal Calibration Module. A calibrator level of 94 dB was used for all measurements. Therefore, the magnitude of the air pressure fluctuation caused by the calibrator, as experienced by the microphone being calibrated, P_{cal}, can be calculated as follows:

$$20 \log\left(\frac{P_{cal}}{20\times10^{-6}}\right) = 94 \text{ [dB]}$$

$$\Rightarrow P_{cal} = 1.00 \text{ [Pa]} \quad \text{(B.1)},$$

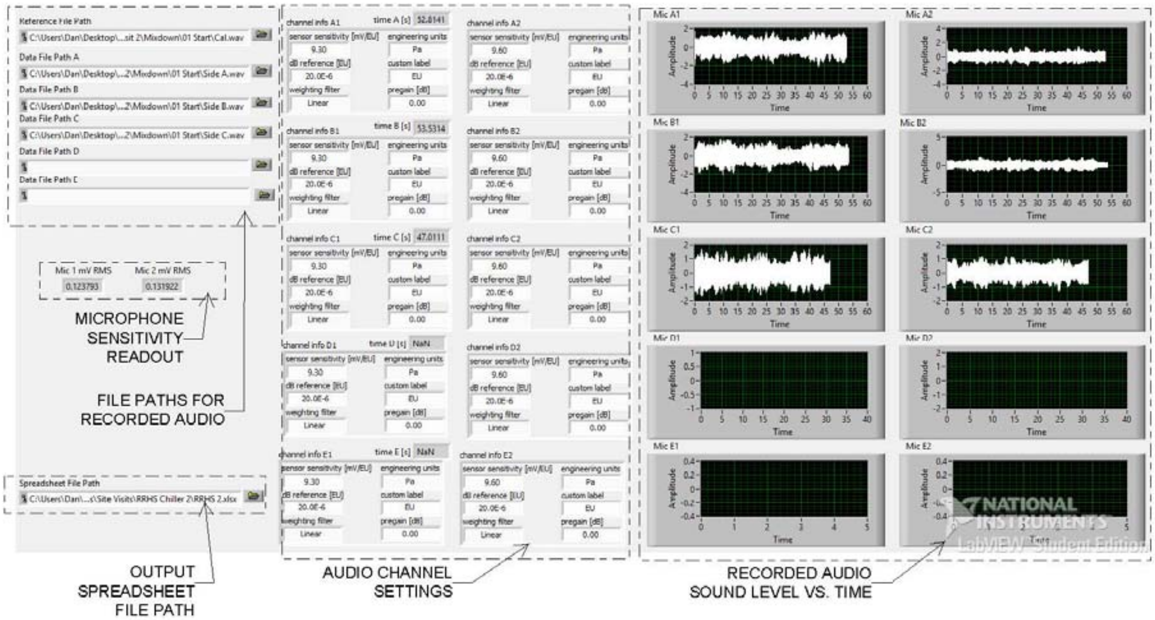


Figure B-2: Custom data acquisition interface using the LabView platform.

It can be similarly shown that if the calibrators other setting, 114 dB, were used, it would result in $P_{cal} = 10.0$ Pa.

RMS voltage of the calibration file, V_{cal}, is measured within the LabView application, and displayed on the user interface. The microphone sensitivity, M, can be calculated as:

$$M = \frac{V_{cal}}{P_{cal}} \text{ [mV/Pa]}.$$

The microphone sensitivity value, M, for both constituent surfaces are passed from the Audio Signal Calibration Module to the five Data Processing Modules, each of which also extracts measurement recordings from one constituent surface from an imported audio file. The core of each Data Processing Module is a custom sub-module, the signal flow diagram for which is shown in Figure B-4.

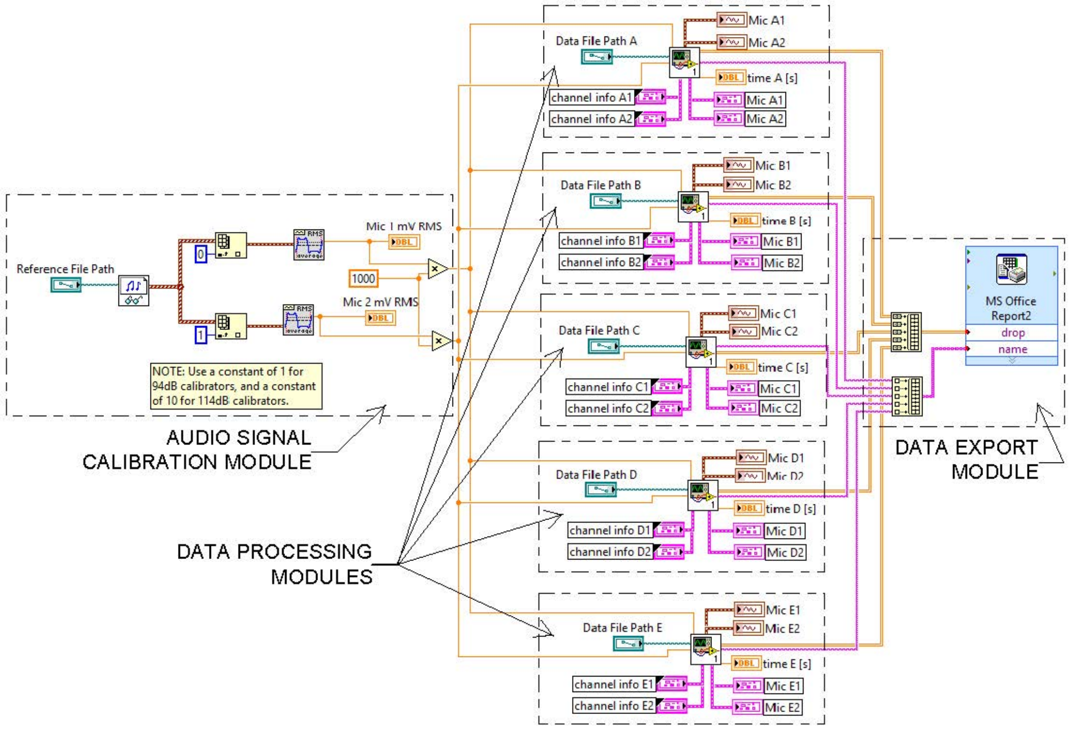


Figure B-3: Custom data acquisition signal flow diagram, within the LabView platform.

Within the sub-module, the M value for each measurement surface is used to calibrate the associated recording, then FFT and weighting operations are performed within LabView to calculate the one-third-octave-band, octave-band, and broadband unweighted, A-weighted, and C-weighted L_{eq} SPL values. These SPL values, along with the length of the recording, and the audio recording file name are then correlated. Finally, the data sets for all files being processed are combined and sent to an XLS format spreadsheet, an example of which is shown in Figure B-5.

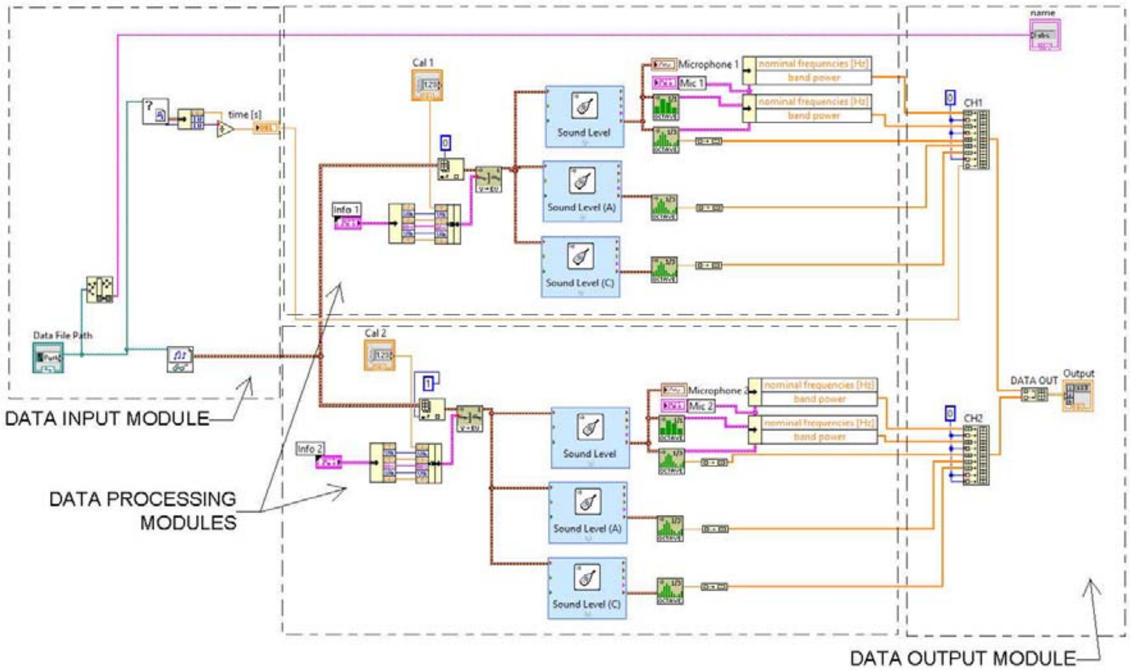


Figure B-4: Custom data processing sub-module signal flow diagram.

The raw data is input into the Data Import Section of the spreadsheet, and the dimensions of the bounding area of the screw chiller, as measured at the site, are input into the Dimensional Information Section. Unless manually overwritten, the inner and outer measurement surface areas are calculated within the spreadsheet as follows:

$$A_* = \frac{H(L+nd_*)}{144},$$

where: A_* [ft^2] ≡ area of the inner or outer measurement surface,

H [in] ≡ vertical dimension of the equipment bounding area,

L [in] ≡ horizontal dimension of the equipment bounding area,

$n = \begin{cases} 1 \text{ if one side was obstructed} \\ 2 \text{ if both sides were unobstructed} \end{cases}$ ≡ number of "free sides", where the microphone boom apparatus was able to be maneuvered to a 45° angle outside the bounding area, and

d_* [in] ≡ distance from the bounding area to the inner or outer measurement microphone.

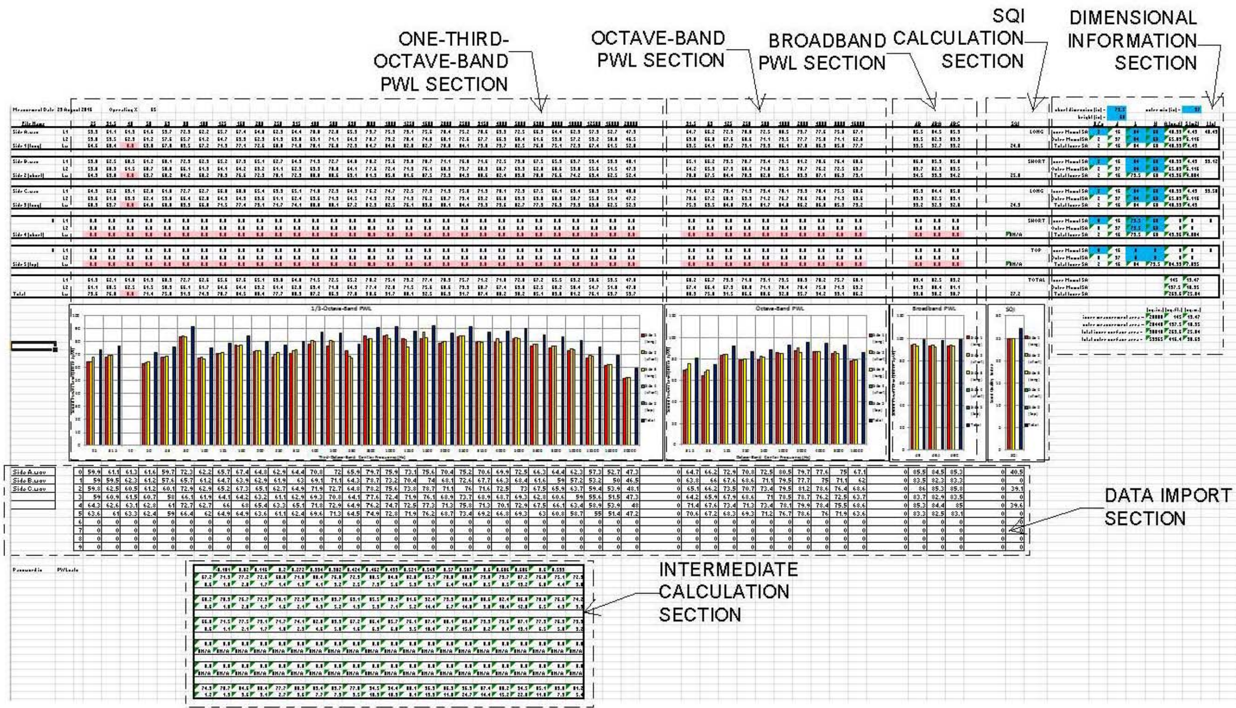


Figure B-5: Typical data processing spreadsheet

The L_{eq} SPL values and the constituent surface areas were used to calculate the one-third-octave-band, octave-band, and broadband unweighted, A-weighted, and C-weighted L_{eq} PWL values, which appear both numerically and graphically in the one-third-octave-band PWL section, the octave-band PWL section, and the broadband PWL section. The SQI is calculated based on the overall one-third-octave PWL spectrum, and displayed in the SQI calculation section. The L_{eq} PWL and SQI values are calculated as per the procedures discussed in Chapter 1, and displayed for each measurement surface, up to a maximum of five, and then summed to overall values.

Appendix C: SQI Rating Indices

The tables contained in this Appendix show the values of I, which are used in Equation (1.17) as a function of both L', the tone adjusted sound levels for each one-third-octave band between 100 Hz and 10,000 Hz, as calculated in Equation (1.16), and the one-third-octave-band center frequencies over the same range.

Interpolation is necessary where the L' values are non-integer, as follows:

$$I = C + [(D - C)(L' - B)] \quad (C.1),$$

where: B = the truncated integer value of L',

C = the index for B, and

D = the index for $B + 1$.

Table C1. Rating Indices

Tone Adjusted Sound Power Level, dB	One-third Octave Band Center Frequencies, Hz 100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
Note: For All One-third Octave Band Sound Power Levels Below 30 dB the Rating Indices Equals 0.																					
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0	0	0	0
35	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0.1**	**0.1**	**0.2**	**0.2**	**0**	**0**	**0**	**0**
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.2	0.2	0.2	0.1	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.2	0.3	0.3	0.2	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.2	0.3	0.3	0.3	0.2	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.3	0.3	0.4	0.4	0.3	0	0	0
40	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0.2**	**0.3**	**0.4**	**0.4**	**0.4**	**0.3**	**0.1**	**0**	**0**
41	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.4	0.4	0.5	0.5	0.4	0.2	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0.1	0.3	0.4	0.5	0.6	0.6	0.4	0.2	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0.1	0.3	0.5	0.6	0.6	0.6	0.5	0.3	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0.2	0.4	0.5	0.6	0.7	0.7	0.6	0.3	0	0
45	**0**	**0**	**0**	**0**	**0**	**0**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.2**	**0.4**	**0.6**	**0.7**	**0.7**	**0.7**	**0.6**	**0.4**	**0.1**	**0**
46	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0.2	0.3	0.5	0.7	0.7	0.8	0.8	0.7	0.5	0.2	0
47	0	0	0	0	0	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.6	0.7	0.8	0.9	0.9	0.7	0.5	0.2	0
48	0	0	0	0	0	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.6	0.8	0.9	1	1	0.9	0.7	0.3	0
49	0	0	0	0	0.1	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.7	0.8	0.8	1	1	0.9	0.7	0.3	0
50	**0**	**0**	**0**	**0**	**0.2**	**0.3**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.5**	**0.7**	**0.9**	**1**	**1.1**	**1.1**	**0.9**	**0.7**	**0.4**	**0.1**
51	0	0	0	0.1	0.2	0.3	0.4	0.4	0.4	0.4	0.4	0.6	0.8	0.9	1.1	1.1	1.1	1	0.8	0.5	0.2
52	0	0	0	0.2	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.6	0.9	1	1.1	1.2	1.2	1.1	0.9	0.6	0.2
53	0	0	0.1	0.2	0.3	0.4	0.6	0.6	0.6	0.6	0.6	0.7	0.9	1.1	1.2	1.3	1.3	1.2	1	0.6	0.3
54	0	0	0.2	0.3	0.4	0.5	0.6	0.6	0.6	0.6	0.6	0.7	1	1.2	1.3	1.4	1.4	1.3	1.1	0.7	0.4
55	**0**	**0**	**0.2**	**0.3**	**0.4**	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.8**	**1.1**	**1.3**	**1.4**	**1.5**	**1.5**	**1.4**	**1.2**	**0.8**	**0.5**
56	0	0.1	0.3	0.4	0.5	0.6	0.7	0.7	0.7	0.7	0.7	0.9	1.2	1.3	1.5	1.6	1.6	1.5	1.4	0.9	0.6
57	0	0.2	0.3	0.4	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.9	1.3	1.4	1.6	1.8	1.8	1.6	1.5	1	0.6
58	0	0.2	0.4	0.5	0.6	0.7	0.9	0.9	0.9	0.9	0.9	1	1.3	1.5	1.8	1.9	1.9	1.7	1.6	1.1	0.7
59	0.1	0.3	0.5	0.6	0.7	0.8	0.9	0.9	0.9	0.9	0.9	1.1	1.4	1.6	1.9	2	2	1.9	1.8	1.2	0.8

Figure C-1: SQI Rating Indices – Part 1(ANSI/AHRI Standard 1140-2012 [3])

Table C1. Rating Indices (Continued)

Tone Adjusted Sound Power Level, dB	One third Octave Band Center Frequencies, Hz																				
	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
60	**0.2**	**0.3**	**0.5**	**0.6**	**0.7**	**0.9**	**1**	**1**	**1**	**1**	**1**	**1.2**	**1.5**	**1.7**	**2**	**2.2**	**2.2**	**2**	**1.9**	**1.4**	**0.9**
61	0.2	0.4	0.6	0.7	0.8	0.9	1.1	1.1	1.1	1.1	1.1	1.3	1.6	1.8	2.2	2.4	2.4	2.2	2	1.5	1
62	0.3	0.5	0.6	0.7	0.9	1	1.1	1.1	1.1	1.1	1.1	1.3	1.7	2	2.4	2.6	2.6	2.4	2.2	1.7	1.1
63	0.3	0.5	0.7	0.8	0.9	1.1	1.2	1.2	1.2	1.2	1.2	1.4	1.8	2.2	2.6	2.8	2.8	2.6	2.4	1.8	1.2
64	0.4	0.6	0.7	0.9	1	1.1	1.3	1.3	1.3	1.3	1.3	1.5	2	2.4	2.8	3	3	2.8	2.6	2	1.4
65	**0.5**	**0.6**	**0.8**	**0.9**	**1.1**	**1.2**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.6**	**2.1**	**2.6**	**3**	**3.2**	**3.2**	**3**	**2.8**	**2.2**	**1.5**
66	0.5	0.7	0.9	1	1.2	1.3	1.5	1.5	1.5	1.5	1.5	1.7	2.3	2.8	3.2	3.4	3.4	3.2	3	2.4	1.7
67	0.6	0.7	0.9	1.1	1.3	1.4	1.6	1.6	1.6	1.6	1.6	1.8	2.4	3	3.4	3.6	3.6	3.4	3.2	2.6	1.8
68	0.6	0.8	1	1.2	1.4	1.5	1.7	1.7	1.7	1.7	1.7	2	2.6	3.2	3.6	3.9	3.9	3.6	3.4	2.8	2
69	0.7	0.8	1.1	1.3	1.5	1.6	1.9	1.9	1.9	1.9	1.9	2.1	2.8	3.4	3.9	4.1	4.1	3.9	3.6	3	2.2
70	**0.8**	**1**	**1.2**	**1.4**	**1.6**	**1.7**	**2**	**2**	**2**	**2**	**2**	**2.3**	**3**	**3.6**	**4.1**	**4.4**	**4.4**	**4.1**	**3.9**	**3.2**	**2.4**
71	0.9	1	1.3	1.5	1.7	1.9	2.1	2.1	2.1	2.1	2.1	2.4	3.2	3.9	4.4	4.7	4.7	4.4	4.1	3.4	2.6
72	0.9	1.1	1.4	1.6	1.9	2	2.3	2.3	2.3	2.3	2.3	2.6	3.5	4.1	4.7	5	5	4.7	4.4	3.6	2.8
73	1	1.2	1.5	1.7	2	2.1	2.5	2.5	2.5	2.5	2.5	2.8	3.7	4.4	5	5.3	5.3	5	4.7	3.9	3
74	1.1	1.3	1.6	1.9	2.1	2.3	2.6	2.6	2.6	2.6	2.6	3	4	4.7	5.3	5.7	5.7	5.3	5	4.1	3.2
75	**1.2**	**1.4**	**1.7**	**2**	**2.3**	**2.4**	**2.8**	**2.8**	**2.8**	**2.8**	**2.8**	**3.2**	**4.3**	**5**	**5.7**	**6.1**	**6.1**	**5.7**	**5.3**	**4.4**	**3.5**
76	1.3	1.5	1.9	2.2	2.4	2.6	3	3	3	3	3	3.5	4.6	5.3	6.1	6.5	6.5	6.1	5.7	4.7	3.7
77	1.4	1.7	2	2.4	2.6	2.8	3.2	3.2	3.2	3.2	3.2	3.7	5	5.7	6.5	7	7	6.5	6.1	5	4
78	1.5	1.8	2.2	2.6	2.8	3	3.5	3.5	3.5	3.5	3.5	4	5.3	6.1	7	7.5	7.5	7	6.5	5.3	4.3
79	1.7	2	2.4	2.8	3	3.2	3.7	3.7	3.7	3.7	3.7	4.3	5.7	6.5	7.5	8	8	7.5	7	5.7	4.6
80	**1.8**	**2.2**	**2.6**	**3**	**3.2**	**3.5**	**4**	**4**	**4**	**4**	**4**	**4.6**	**6.1**	**7**	**8**	**8.7**	**8.7**	**8**	**7.5**	**6.1**	**5**
81	2	2.4	2.8	3.2	3.5	3.7	4.3	4.3	4.3	4.3	4.3	5	6.5	7.5	8.7	9.3	9.3	8.7	8	6.5	5.3
82	2.2	2.6	3	3.5	3.7	4	4.6	4.6	4.6	4.6	4.6	5.3	7	8	9.3	10	10	9.3	8.7	7	5.7
83	2.4	2.8	3.2	3.7	4	4.3	4.9	4.9	4.9	4.9	4.9	5.7	7.5	8.7	10	11	11	10	9.3	7.5	6.1
84	2.6	3	3.5	4	4.3	4.6	5.3	5.3	5.3	5.3	5.3	6.1	8	9.3	11	11	11	11	10	8	6.5
85	**2.8**	**3.2**	**3.7**	**4.3**	**4.6**	**5**	**5.7**	**5.7**	**5.7**	**5.7**	**5.7**	**6.5**	**8.7**	**10**	**11**	**12**	**12**	**11**	**11**	**8.7**	**7**
86	3	3.5	4	4.6	5	5.4	6.1	6.1	6.1	6.1	6.1	7	9.3	11	12	13	13	12	11	9.3	7.5
87	3.3	3.7	4.3	5	5.4	5.9	6.5	6.5	6.5	6.5	6.5	7.5	10	11	13	14	14	13	12	10	8
88	3.6	4	4.6	5.4	5.9	6.4	7	7	7	7	7	8	11	12	14	15	15	14	13	11	8.7
89	3.9	4.3	5	5.9	6.4	6.9	7.5	7.5	7.5	7.5	7.5	8.7	11	13	15	16	16	15	14	11	9.3

Figure C-2: SQI Rating Indices – Part 2(ANSI/AHRI Standard 1140-2012 [3])

Table C1. Rating Indices (Continued)

Tone Adjusted Sound Power Level, dB	One third Octave Band Center Frequencies, Hz																				
	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
90	**4.2**	**4.6**	**5.4**	**6.4**	**6.9**	**7.5**	**8**	**8**	**8**	**8**	**8**	**9.3**	**12**	**14**	**16**	**17**	**17**	**16**	**15**	**12**	**10**
91	4.6	5	5.9	6.9	7.5	8	8.6	8.6	8.6	8.6	8.6	10	13	15	17	19	19	17	16	13	11
92	5	5.4	6.4	7.5	8	8.7	9.2	9.2	9.2	9.2	9.2	11	14	16	19	20	20	19	17	14	11
93	5.4	5.9	6.9	8	8.7	9.3	9.8	9.8	9.8	9.8	9.8	11	15	17	20	21	21	20	19	15	12
94	5.9	6.4	7.5	8.7	9.3	10	10.6	10.6	10.6	10.6	10.6	12	16	19	21	23	23	21	20	16	13
95	**6.4**	**6.9**	**8**	**9.3**	**10**	**11**	**11.3**	**11.3**	**11.3**	**11.3**	**11.3**	**13**	**17**	**20**	**23**	**24**	**24**	**23**	**21**	**17**	**14**
96	6.9	7.5	8.7	10	11	11	12	12	12	12	12	14	19	21	24	26	26	24	23	19	15
97	7.5	8.3	9.3	11	11	12	13	13	13	13	13	15	20	23	26	28	28	26	24	20	16
98	8.3	9.1	10	11	12	13	14	14	14	14	14	16	21	24	28	30	30	28	26	21	17
99	9.1	10	11	12	13	14	15	15	15	15	15	17	23	26	30	32	32	30	28	23	19
100	**10**	**11**	**11**	**13**	**14**	**15**	**16**	**16**	**16**	**16**	**16**	**19**	**24**	**28**	**32**	**35**	**35**	**32**	**30**	**24**	**20**
101	11	11	12	14	15	16	18	18	18	18	18	20	26	30	35	37	37	35	32	26	21
102	11	12	13	15	16	17	19	19	19	19	19	21	28	32	37	40	40	37	35	28	23
103	12	13	14	16	17	19	20	20	20	20	20	23	30	35	40	42	42	40	37	30	24
104	13	14	15	17	19	20	21	21	21	21	21	24	32	37	42	45	45	42	40	32	26
105	**14**	**15**	**16**	**19**	**20**	**21**	**23**	**23**	**23**	**23**	**23**	**26**	**35**	**40**	**45**	**47**	**47**	**45**	**42**	**35**	**28**
106	15	16	17	20	21	23	24	24	24	24	24	28	37	42	47	50	50	47	45	37	30
107	16	17	19	21	23	24	26	26	26	26	26	30	40	45	50	55	55	50	47	40	32
108	17	19	20	23	24	26	28	28	28	28	28	32	42	47	55	60	60	55	50	42	35
109	19	20	21	24	26	28	30	30	30	30	30	35	45	50	60	63	63	60	55	45	37
110	**20**	**21**	**23**	**26**	**28**	**30**	**32**	**32**	**32**	**32**	**32**	**37**	**47**	**55**	**63**	**67**	**67**	**63**	**60**	**47**	**40**
111	21	23	24	28	30	32	34	34	34	34	34	40	50	60	67	71	71	67	63	50	42
112	23	24	26	30	32	35	37	37	37	37	37	42	55	63	71	75	75	71	67	55	45
113	24	26	28	32	35	37	39	39	39	39	39	45	60	67	75	80	80	75	71	60	47
114	26	26	30	35	37	40	42	42	42	42	42	47	63	71	80	86	86	80	75	63	50
115	**28**	**30**	**32**	**37**	**40**	**42**	**45**	**45**	**45**	**45**	**45**	**50**	**67**	**75**	**86**	**93**	**93**	**86**	**80**	**67**	**55**
116	30	32	35	40	42	45	49	49	49	49	49	55	71	80	93	100	100	93	86	71	60
117	32	35	37	42	45	47	52	52	52	52	52	60	75	86	100	108	108	100	93	75	63
118	35	37	40	45	47	50	56	56	56	56	56	64	80	93	108	116	116	108	100	80	67
119	37	40	42	47	50	55	60	60	60	60	60	69	86	100	116	125	125	116	108	86	71
120	**40**	**42**	**45**	**50**	**55**	**60**	**64**	**64**	**64**	**64**	**64**	**74**	**93**	**108**	**125**	**133**	**133**	**125**	**116**	**93**	**75**

Figure C-3: SQI Rating Indices – Part 3(ANSI/AHRI Standard 1140-2012 [3])

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